COMPARING DUAL DRAINAGE MODEL (DDM) WITH SWMM: A CASE STUDY IN JOHN STEET WATERSHED, CHAMPAIGN IL

BY

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THESIS

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ABSTRACT

This study investigated the capacity and uncertainty of Dual Drainage Model (DDM) in urban storm water management by modeling dual drainage system in John Street watershed, Champaign IL under major and minor storms, by comparing the model performance of DDM to Storm Water Management Model (SWMM) and by examining the sensitivity of Green Infrastructure (GI) application in DDM.

Considering storm water dual drainage during severe storms could reduce property damage and economic loss from flooding. Available dual drainage models occupy heavy computational burden, compel demanding setup efforts, or have no interactions between surface and underground flow. Instead, DDM is a one-dimensional (1D) hydrologic-hydraulic model, including innovative surface modules and a traditional SWMM sewer engine. Its execution file is merely 3.14-MB, and the program is easy to set up with auxiliary data from Geographic Information System (GIS). However, there was only one case study and no assessment on model performance.

Therefore, in this study a 458-acre dual drainage system in John Street watershed was assessed by DDM, comprising 26 blocks, 76 streets, 66 inlets, 68 manholes and 67 conduits. The storm water runoff from overland, on street and in sewer were compared to those in SWMM under 2-year, 10-year, 50-year and 100-year 60-minute rainfall. Hydrograph and statistical errors were used to visualize and quantify the model performance. A sensitivity analysis for GI was conducted under five scenarios with different catchment and sewer conditions. Results showed DDM worked better under major high-intensity storms, by providing the closest total runoff volume as SWMM (-1.21% error) and a conservative estimation of surface peak flow. Unit change in GI properties (percent impervious, suction head, hydro conductivity, porosity, etc.) resulted in up to 0.3 unit change of overland runoff during minor storms, supporting that DDM is sensitive to GI. More case studies with real observatory data are recommended for DDM future assessment.

Former observations suggest: i) using DDM for urban dual drainage modeling during major storms and ii) adding GI module in DDM future development. This study is of importance to hydrologist, engineers and researchers because DDM provides detailed flow properties

and interactions. It is also critical to city builders, government and residents in terms of reducing economic loss by identify flooding area and causes.

ACKNOWLEDGEMENT

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CHAPTER 1 INTRODUCTION

1.1 Research Question

This study focused on modeling dual drainage system in John Street Watershed, Champaign IL by DDM during different rain events. The goal of this study is to analyze the capacity and uncertainty of DDM, in terms of model performance compared to SWMM and its future applicability to GI.

The following research questions were asked according to the primary goal.

- What is the hydrological and hydraulic response of dual drainage system in John Street Watershed?
- How is the model performance under minor and major storms?
- What is the advantage of DDM compared to SWMM, in terms of model method?
- What is the sensitivity of DDM inputs, especially GI properties?
- Does DDM work better than SWMM? If so, under what condition and why?
- What is the limitation of DDM? Could that be improved in future?

1.2 Why Focus on Urban Dual Drainage

About 27.6 billion gallons of storm water runoff are generated daily from urbanized areas. (US EPA, 2002; US EPA, 2004) In order to provide convenient use of the right-of-way, municipal stormwater drainage system is designed to carry runoff from upstream land to downstream watercourses. It consists primarily of underground sewer network, which was sized economically accommodating minor low-intensity storms.

Today, with increasing frequency of major extreme storms, the existing drainage system could no longer convey water out of urban area promptly due to its inadequate capacity. More than 700 cities in the United States are facing frequent combined sewer overflows (CSOs). Chicago encounters CSOs over 100 days per annum, not to mention the basement flooding. This persistence of flooding during major storms brought big concerns to both residents and city builders, regarding present value of public and private properties.

Dual Drainage system was recommended to assess flooding on major system during major storms. (Djordjevic, Prodanovic, Maksimovic, Ivetic, & Savic, 2005; Djordjević , Prodanović, & Maksimović, 1999) It intends to minimize the property damage and economic loss by providing a convenient overland flow path with adequate storage. It is necessary for flood risk assessment under concurrent condition.

1.3 Understanding Urban Dual Drainage

Evaluating the surface system with inclusion of the sewer system under major high-intensity storms was referred to as dual drainage concept. (Djordjevic, Prodanovic, Maksimovic, Ivetic, & Savic, 2005; Djordjević , Prodanović, & Maksimović, 1999) Figure 1 shows the interaction of surface and sewer flow in dual drainage system when flooding. (Schmitt, Martin, & Norman , 2004)

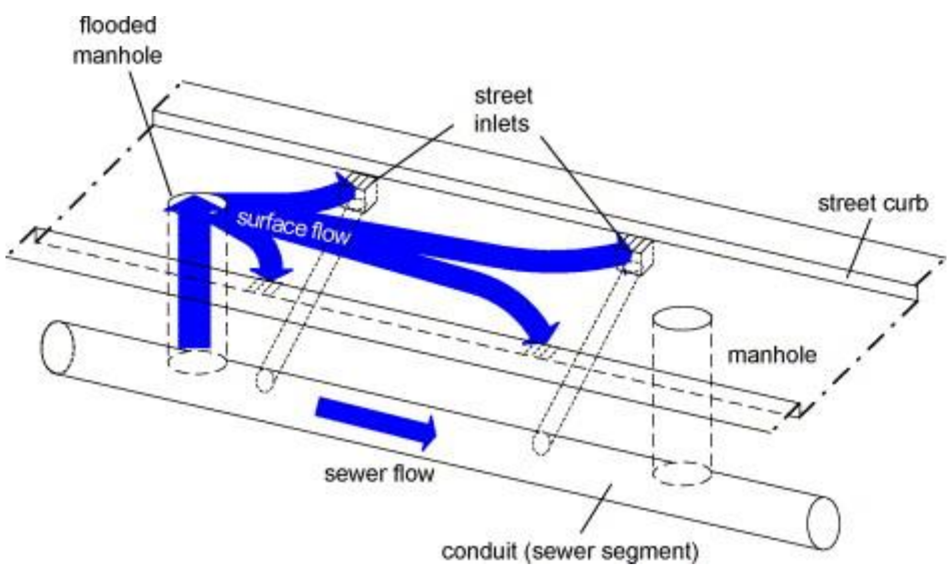


Figure 1 The interaction between surface and sewer flow in dual drainage system when flooding (Schmitt, Martin, & Norman , 2004)

The minor system consists primarily of underground sewer pipes, which is designed to convey storm water runoff to a sewer outlet under 1-year to 10-year minor storms. Conversely, major system, comprising primarily the overland flow path like street and swales, is designed to convey floods from overflowed minor system under severe storms like 100-year storm. Considering only minor system would underestimate surface storage capacity and potential flooding risk during severe storms. Considering mainly major system could prevent loss of life and protect properties from damage, but it also increases the budget and requires more infrastructure space. Thus, combining both systems, also known as dual drainage design, could provide quick and reliable underground sewer drainage during minor storms and adequate flooding drainage on surface land during major storms.

However, compared to the conventional minor sewer system modeling, dual drainage modeling involves a wide array of complex. Firstly, it requires decision making on overland flow path, especially for 1D major overland system. (Simões, et al., 2011; Djordjevic, Prodanovic, Maksimovic, Ivetic, & Savic, 2005) Secondly, it involves more efforts in model development, in terms of data and time. (Gironás, Roesner, & Davis, 2009) Thirdly, it may use large computation resources for high resolution results, particularly in 2D major overland system. (Chen, Leandro, & Djordjević, 2015; Ghimire, et al., 2012; Jahanbazia & Eggera, 2014; Schmitt, Martin, & Norman , 2004) The tradeoffs are highly dependent on the area of interest.

SWMM is one of the comprehensive and widely accepted minor system models. It also allows for dual drainage modeling, although the setup requires prohibitively demanding efforts. (Gironás, Roesner, & Davis, 2009) DDM is a one-dimensional (1D) hydrologic-hydraulic model for simulating dual drainage in urban areas (Nanía, León, & García, 2015). It consists of four modules: rainfall-runoff transformation, 1D flow routing on a street network, inlet interception and sewer routing with SWMM engine. It is an innovative model for major system, while incorporating SWMM minor system engine. The application itself is only 3.14-MB and is easy to set up. It has independent script for each individual model, which facilitates future program implementation. Programmers could easily modify the script of targeted individual module in DDM. For example, overland module could incorporate rain gardens and street module could have pervious pavement. However, there was only one case study and no assessment on the model performance. More studies are called for DDM future application.

1.4 Importance to Civil and Environmental Engineering

The importance of dual drainage system to civil and environment engineering is that it could help researchers to study the hydrological and hydraulic behavior of major storm runoff. It could be a great tool for city planners to identify urban flooding areas during major storms. It could prevent property damage beforehand so as to reduce the economic loss from residents and government.

The importance of this study to Civil and Environmental Engineering is that it fills the gap between dual drainage concept and usable dual drainage model. DDM is an innovative model and easy to set up. The independent module in DDM also allows for modification on different area of interests. It has the potential of application but has not been fully assessed. This study filled this gap by evaluating the potential of DDM.

1.5 Contributions

The main contributions of this study are threefold. Firstly, this study modeled dual drainage system and evaluated its performance. Modeling dual drainage system is still new in hydrological and hydraulic studies. Not a lot models and case studies were done and tested before. This study applied dual drainage system in John Street Watershed Champaign, IL by DDM and SWMM. It worked under both major and minor storms. DDM presented detailed flow time series in surface major system and sewer minor system. The surface and sewer interaction, restricted by inlet interception rate in DDM, was also successfully demonstrated in the results. It could be useful to dual drainage system study.

Secondly, this study showed the potential of DDM in dual drainage modeling during major storms, by generating the closest total overland runoff volume as SWMM and providing a conservative estimation of street flow. Major system performance is the key to flood assessment. It accords with the concerns of government and residents in economic loss. In addition, DDM presented high GI sensitivity under minor storms. DDM could assess the influence from GI properties quantitatively in terms of surface runoff and sewer runoff. It opens up the possibility of evaluation of GI in dual drainage system under major storms.

Thirdly, this study provided a GIS tool box and some python scripts, which could automatically extrapolate raw data and generate input files for the model. With some modifications to the area of interest, it could save researchers a lot of model set up time and efforts.

1.6 Organization of This Thesis

The chapters of this thesis are organized as follows:

- Chapter 1 introduces the research questions, the importance of dual drainage system, the concept of dual drainage system and the contribution of this study.
- Chapter 2 gives a literature review on previous studies of dual drainage model, GI and criteria for watershed model evaluation.
- Chapter 3 presents detailed data inputs and methods used in this study. This chapter starts with the data collection for climate, catchment and sewer system. Following that, the basic model principles for SWMM and DDM are introduced, with extra highlighting on the model difference. Afterwards, hydrograph and statistical error are suggested for result assessment. Finally, sensitivity analysis is proposed to evaluate GI potential in DDM.
- Chapter 4 introduces the tools and models used in this study. Dual drainage system of John Street Watershed were built in SWMM and DDM. A GIS Toolbox including python based scripts were used to generate input files from GIS. User Interfaces and operation window for DDM and SWMM were also presented.
- In Chapter 5, three models introduced in Chapter 4, as DDM, SWMM connecting sewer and SWMM connecting street, were tested under four rain scenarios at John Street Watershed, Champaign IL. Four rain storms, 2-year 60-minute rain, 10-year 60-minute rain, 50-year 60-minute rain and 100-year 60-minute rain, were adopted from Huff distribution. The results were interpreted independently in terms of overland flow, street flow and sewer flow. The difference within models and between models were illustrated by hydrographs and statistical errors. In addition, a sensitivity analysis examined the potential for DDM’s application on GI.
- In Chapter 6, the potential of DDM is examined in four aspects, DDM model method advantage, reaction to storms, effects within DDM and GI application. DDM demonstrated high potential for major storm modeling. It was sensitive to GI properties under minor storms.
- Chapter 7 concludes the results and discussion. It states the limitation of this study and also makes recommendation for future development.

CHAPTER 2 LITERATURE REVIEW

The goal of this study is to analyze the feasibility of DDM in urban flooding problems and GI application. This literature review summarized past works related to this study. It focuses on three parts, current dual drainage models, GI and model comparison criteria.

2.1 Current Urban Dual Drainage Models

Dual drainage modeling involves a wide array of complex. It incorporates major surface system modeling with traditional minor sewer system modeling. Most works have been done in major system model improvement, including both 1D and 2D approaches.

Schmitt, Martin, & Norman, (2004) developed a dual drainage tool "RisUrSim" for drainage cost effective management. It could generate detailed 2D surface runoff but require abundant computation resources. It put emphasis on the interaction between surface and sewer flow but require calibration of routing step. So this model could only be applied in small area. Jahanbazia & Eggera, (2014) built a 2D overland model HYSTEM-EXTRAN 2D. It also considered surface and sewer flow interaction. However, it was only recommended to be used in the flood-prone area of the target site due to high computation burden. Nevertheless, the input data for 2D models are not available for most sites.

Conversely, CADDIES uses cellular automata technique to generate 2D surface runoff. (Ghimire, et al., 2012) It is a 2D major system model that is fast, detailed and computation burden free, quite opposite to the conventional ones. This technique has been applied in several studies and showed promising results. (Liu, et al., 2015; Ghimire, et al., 2012) However, the corresponding sewer minor system model is still under development.

Compared to 2D models, 1D model generates relative high resolution results with reduced computation burden. EPA SWMM is one of the comprehensive and widely accepted drainage models. It allows 1D dual drainage modeling, by adding street network parallel to the existing sewer system. However, the setup of dual drainage system in SWMM requires prohibitively demanding efforts. (Gironás, Roesner, & Davis, 2009) Researchers need to delineate the overland flow path beforehand, putting time and efforts in literature reviews and decision making. In summary, 2D model occupies more computation burden and 1D model requires more up-fronting efforts. The tradeoffs between them are highly dependent on the area of interest.

DDM is a 1D hydrologic-hydraulic model for simulating dual drainage in urban areas. (Nanía, León, & García, 2015) The application itself is only 3.14-MB and is easy to set up. It consists of four modules: rainfall-runoff transformation, 1D flow routing on street network, inlet interception and sewer routing by SWMM engine. It is an innovative model for major system, while incorporating SWMM minor system engine. The consideration of inlet interception restriction between surface and sewer interaction is also supported by works from Chen, Leandro, & Djordjević, (2015). In addition, DDM used Fortran language and had individual script section for each module, which facilitates future model implementation. However, there was only one case study and no assessment on the model performance. More studies are called for DDM future application.

2.2 GI

GI uses vegetation and soil to mimic natural hydrological process for urban storm water drainage. Runoff is absorbed and filtered on site by soil. Flow velocity is reduced by vegetation cover. It is an infiltration based method, also known as Low Impact Development (LID) and Best Management Practice (BMP). Typical GI includes Downspout Disconnection, Rain Gardens, Planter Boxes, Permeable Pavements, Green Roofs and Infiltration Trench.

GI showed high potential for urban storm water management from case studies in Portland, Nashville, New York, Prince George's County, etc. (Jawdy, Reese, & Parker, 2010; Madden, 2010) GI was even adopted to conquer CSO problems instead of tradition grey infrastructure in Philadelphia. (Madden, 2010) It has been implemented in SWMM 5 engine since 2005, denoted as LID. (Rossman, 2015) Except SWMM, none of the existing dual drainage models include GI application.

2.3 Model Comparison Criteria

Watershed models are powerful tools for watershed hydrologic process evaluation and water resources management. Comprehensive guidance and criteria are available to assess the model performances. (Moriasi, et al., 2007; ASCE, 1993; Green & Stephenson, 1986;

Nash & Sutcliffe, 1970; Yen, 1981) Model comparison criteria related to this study were selected and explained in the following three aspects.

First of all, flood studies and urban drainage studies are frequently single event studies, (Green & Stephenson, 1986) instead of continuous long-term simulation. The objectives of single event simulation are the determination of peak flow rate and timing, flow volume and recession curve shape. (ASCE, 1993; Moriasi, et al., 2007) In this study, these parameters were paid special attention to when comparing model performances.

Secondly, quantitative statistics and graphical techniques are both recommend to be utilized in model evaluation. (ASCE, 1993; Moriasi, et al., 2007; Green & Stephenson, 1986) In this study, hydrograph works as a visual comparison of time-series data and a first overview of model performance, while several statistical errors are selected to quantify model distinction under different scenarios as shown in Table 4.

In addition, it is necessary to separate the surface flow from sewer flow in the same model simulation. (Yen, 1981; Green & Stephenson, 1986) The surface flow is related and only related to hydrologic properties of climate and catchment basin. Conversely, the sewer flow is a function of hydraulic properties of sewer network. These two parts are clearly separated module, unless the sewer manholes are surcharged and overflowed.

CHAPTER 3 METHODOLOGY

Detailed data inputs and methods are presented within Chapter 3. This chapter starts with the data collection for climate, catchment and sewer system. Following that, the basic model principles for SWMM and DDM are introduced, with extra highlighting on the model difference. Afterwards, hydrograph and statistical error are suggested for result assessment. Finally, sensitivity analysis is proposed to evaluate GI potential in DDM.

3.1 Data Collection

For this study, climate data, soil properties and catchment characters were collected for overland major system, as shown in Figure 2. Sewer pipeline network data was collected for sewer minor system.

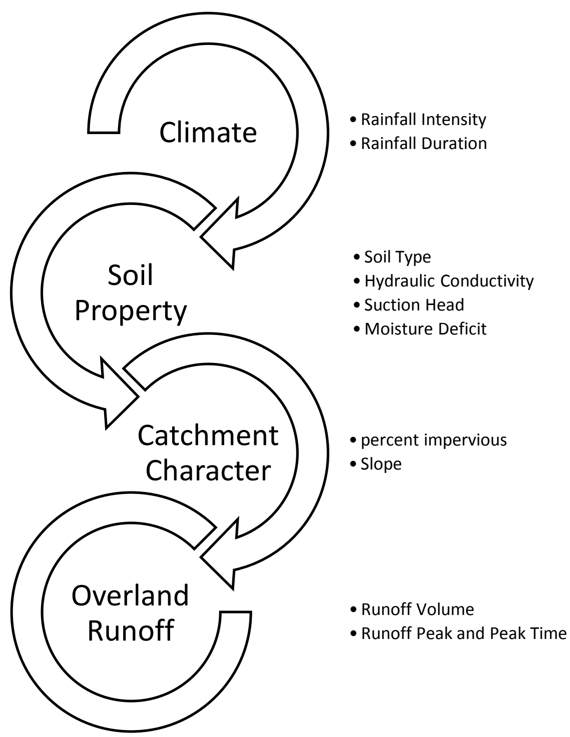


Figure 2 DDM Overland module data inputs and outputs, including climate data, soil property, catchment character and overland runoff

3.1.1 Climate

The rainfall data used in this study were hypothesized heavy rainstorms in east Illinois. (Huff & Angel, 1989) Single event simulation was favorably selected to model flooding problems. (ASCE, 1993) 60-minute short duration storms were utilized. 2-year, 10-year, 50-year and 100-year frequency storms were chosen to assess the model reaction to both minor and major storms. The 2-year storm is minor low-intensity storm, and the 100 year storm is major high-intensity storm.

The total rainfall depth and the rainfall distribution were adopted from works by Huff & Angel (1989) and Huff (1990), which were recommended for use in conjunction. Huff & Angel (1989) determined the frequency distributions of storms in Illinois for different duration and recurrence intervals. The total rainfall depths used in this study are presented in Table 1. Median time distribution of heavy rainfall was adapted to the area of interest. (Huff, 1990) First-quartile storms were used under 60-minute durations. Figure 3 shows the rainfall distribution hydrograph of a 100-year storm. Storms with other return periods share similar shape as Figure 3, but with smaller intensity.

Table 1 Mean rainfall depth in East Illinois for 2-year, 10-year, 50-year and 100-year 60-minute storm (Huff & Angel, 1989) (unit in inches)

Return Period	2-year	10-year	50-year	100-year
60-minute	1.41	2	2.74	3.11

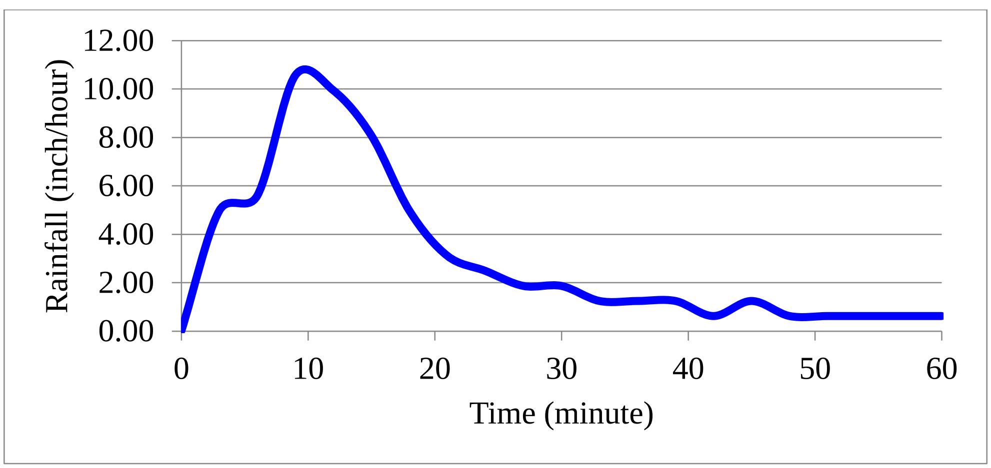


Figure 3 Hypothetical rainfall distribution of 100-year 60-minute first-quartile storm in East Illinois, adapted from the work of Huff (1990)

3.1.2 Catchment

John Street Watershed is a flood-prone area located southwest of downtown Champaign, as shown in Figure 4, covering around 458 acres. This watershed is fully developed with both residential area in the west and urbanized area in the east. Surface runoff from the north and the south flow to John Street by gravity, entering the trunk sewers under it. Then the sewer drain from west to east in John Street Trunk Sewer and merge into Neil Street Trunk Sewer. Afterwards, the sewer outflow is discharged into the southwest branch of boneyard Creek. Localized flooding has been problematic due to the frequency and severity of flooding events, especially at the intersection of Daniel and Willis shown in Figure 5 and north of John Street between Lynn Street and Elm Street. (Clark Dietz, Inc., 2009)

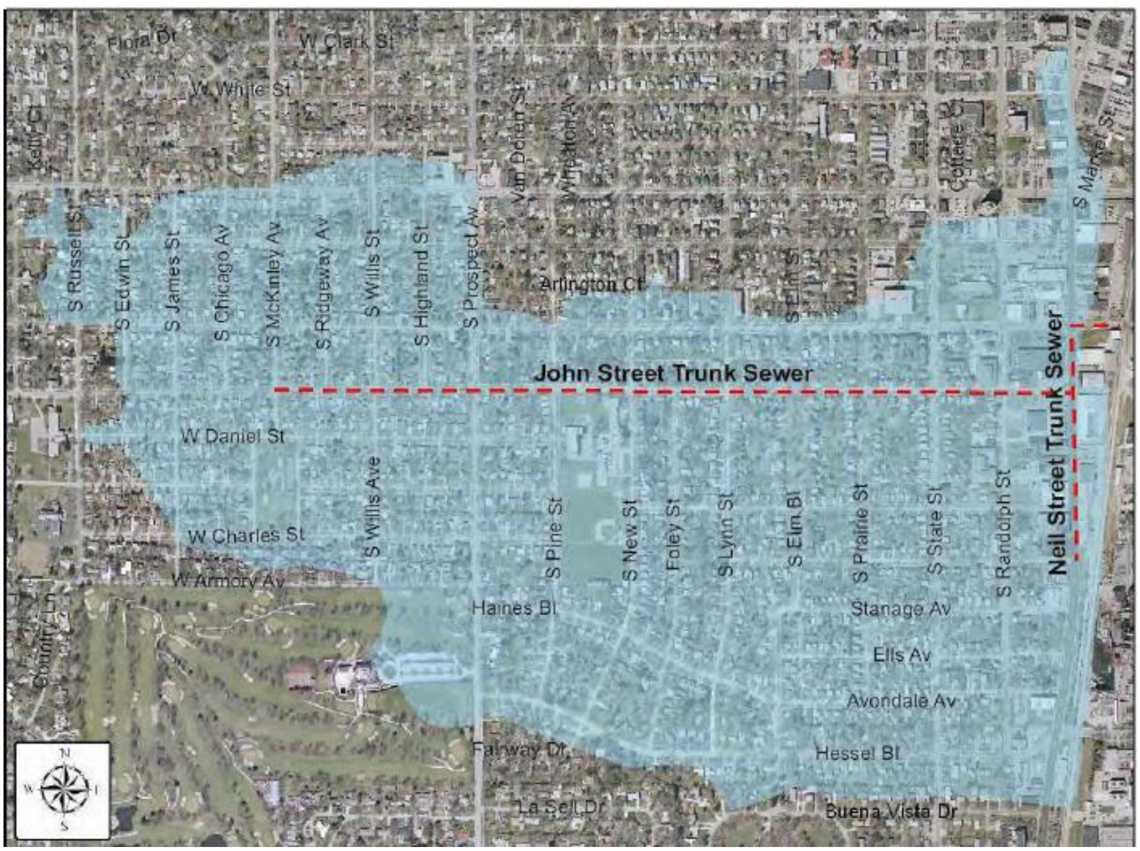


Figure 4 John Street Watershed with Trunk Sewer Pipes under John Street and Neil Street (Clark Dietz, Inc., 2009)

Figure 5 Flood-prone area in John Street Watershed (Clark Dietz, Inc., 2009)

In this study, only the flood-prone area in John Street Watershed was modeled, as shown in Figure 6. The John Street Watershed layout in GIS complies catchment delineation shapefiles, surface elevation layer and sewer network shapefiles. The background image of Champaign County was imported from 2011 Illinois Department of Transportation (IDOT) Orthophotography. (IDOT, 2014) The ground spatial resolution is 1-ft × 1-ft per pixel. Streets and blocks were delineated according to it. Surface elevation in Champaign County was imported from the Digital Elevation Model (DEM) by Light Detection and Ranging (LiDAR) technology. (ILHMP, 2014) The elevation in John Street Watershed is decreasing from west to east, as shown by high-elevation blue color and low-elevation red color in Figure 6. In addition, Sewer layout, including manholes, inlets and sewer pipelines were adjusted from the SWMM model provided by Champaign County. Inlet locations were double checked by Google Map Street View and onsite visit. The street geometry in Figure 7 was assigned to the whole watershed.

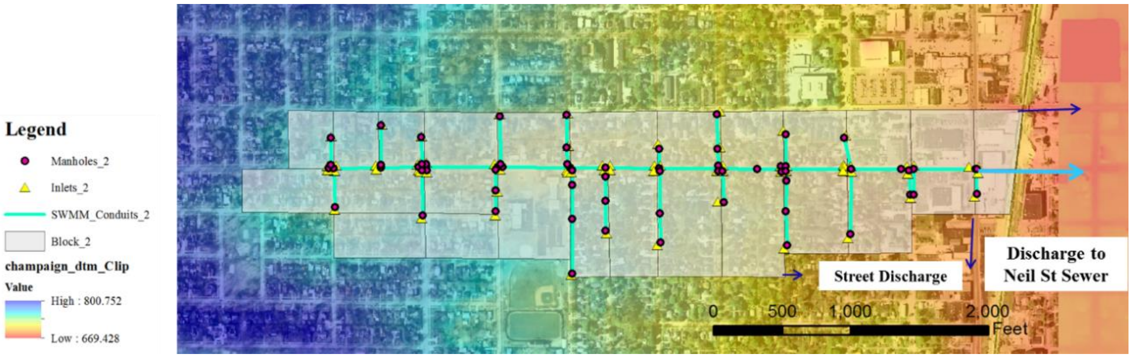


Figure 6 John Street Watershed layout in GIS (circle represents sewer manhole, triangle represents sewer inlets, blue line represents sewer pipe and rectangular represents catchment; background image from IDOT (2014); surface elevation from ILHMP (2014), blue represents higher elevation and red represents lower elevation)

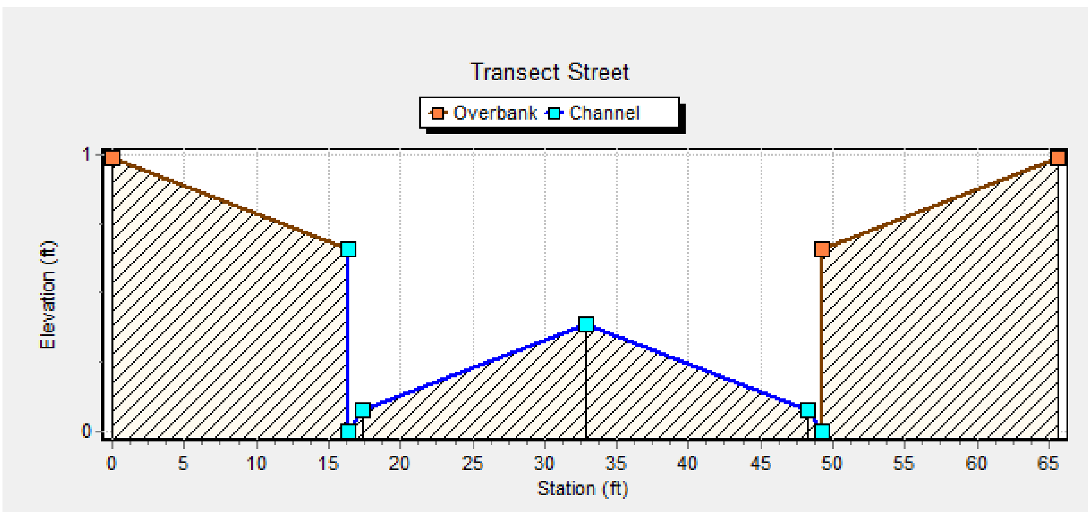


Figure 7 Street transect geometry (not to scale) assigned to John Street Watershed

The area of each block was automatically recorded in GIS shapefile attribute table. The impervious area include the area of rooftops, sidewalks, bike paths and streets in each block. It was measured by GIS Measure Tool and averaged three times for each block in order to generate an accurate estimation. The percent impervious for each block was calculated as the total impervious area over the area of each block.

More than 75% of the pervious land in John St watershed is covered by silt loam soil, while the other quartile is silty clay loam, according to online soil survey in John Street

Watershed. (USDA, 2014) To represent the worst drainage condition, Soil properties of silt loam, as shown in Table 2, were assigned to all pervious area in John Street Watershed.

Other hydraulic properties are presented in Table 3. The impervious area in John St watershed was covered mainly by brick with cement mortar. The pervious area was covered by short prairie grass. Table 3 shows the corresponding manning's n and depression storage for both pervious and impervious area. In addition, the average street slope 1.09% was assigned to both impervious and pervious surfaces. This street slope was calculated from the surface elevation data in GIS. (ILHMP, 2014)

Table 2 Hydraulic soil properties for Silt Clay Loam (Rawls, Brakensiek, & Saxton, 1982)

Properties	Unit	Value	Range
Effective Saturation (Total porosity)	/	0.501	0.42-0.582
Effective porosity	/	0.486	0.394-0.578
Saturated hydraulic conductivity	inch/hour	0.26	/
Suction head	inch	6.69	/

Table 3 Hydraulic catchment properties in pervious and impervious areas of John Street Watershed (Rossman, 2010)

Properties	Unit	Value	Range
Pervious Manning's n	/	0.15	/
Impervious Manning's n	/	0.014	/
Pervious Depression Storage	inch	0.075	0.05-0.1
Impervious Depression Storage	inch	0.15	0.1-0.2

3.1.3 Sewer System

Sewer network was manually created according to Proposed John Street Drainage Improvements Phase 1 and Phase 2. (City of Champaign, 2009) There are 68 sewer manholes, 67 sewer conduits and one outfall in John Street Watershed. 19 of the sewer pipes are main truck sewer pipes; others are minor pipes. The invert elevation represented retrofit John Street (60in pipes) condition, instead of the original one (30in). The ground elevation was chosen as the higher one between GIS DEM data and Proposed John Street Drainage Improvements reports. (City of Champaign, 2009)

3.2 Model Principle

3.2.1 SWMM

SWMM is a dynamic hydrology-hydraulic storm water simulation model. (Rossman, 2010) The overland flow module operates on a collection of catchment areas that receive precipitation and generate runoff. The sewer routing module transports this runoff through a system of pipes to sewer outlet. Hydrologic and hydraulic key features are briefly introduced in the following Sections.

3.2.1.1 Hydrologic process

The hydrologic model in SWMM transforms rainfall to overland runoff on two independent pervious and impervious surfaces, considering infiltration loss. SWMM assumes catchment as a rectangular surface with constant slope and width, discharging to a single outlet, as shown in Figure 8. Hydrologic overland flow is routed as a nonlinear reservoir as shown in Figure 9. (Rossman, 2010)

The basic equation in hydrological process is the conservation of mass.

$$\frac{\partial d}{\partial t} = i - e - f - q = i - e - f - \frac{1.49WS^{\frac{1}{2}}}{An}(d - d_s)^{\frac{5}{3}}$$

Where

d = overland flow depth (ft)

d_s = depression storage (ft)

t = time step (s)

i = rate of rainfall + snowmelt (ft/s)

e = surface evaporation rate (ft/s)

f = infiltration rate (ft/s)

q = runoff rate (ft/s)

W = overland flow width (ft)

S = slope (ft/ft)

n = manning's coefficient

In this study, SWMM used Green-Ampt method to calculate infiltration loss during hydrological process. Green-Ampt in SWMM considers initial deficit, which is a fraction of soil volume that is initially dry. It was set to 0 to accommodate DDM.

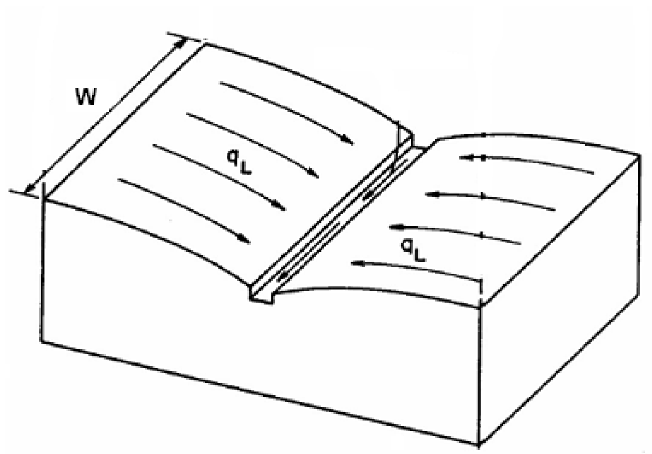


Figure 8 SWMM catchment scheme, as rectangular surface with constant slope and width, discharging to a single outlet (Rossman, 2010)

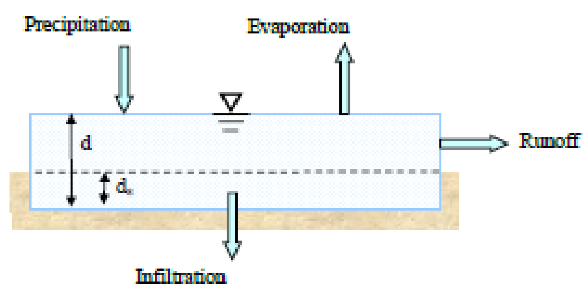


Figure 9 Nonlinear reservoir model for hydrological process in SWMM (Rossman, 2010)

3.2.1.2 Hydraulic process

There are three flow routing options in SWMM, as steady flow, kinematic wave and dynamic wave. (Rossman, 2010) Dynamic wave, also known as Saint-Venant equations, solves two partial differential equations for both continuity and momentum. It takes into account acceleration (inertia), pressure forces, gravitational forces and friction forces. Kinematic wave is a simplification of full Saint-Venant equations by reducing acceleration and pressure forces. This reduction causes limitations, such as less attenuating in flood peak, error for downstream control and backwater effect with mild slope.

Dual drainage model in SWMM only allows for dynamic wave routing. (Gironás, Roesner, & Davis, 2009) However, the difference of overland flow in John Street Watershed by SWMM is less than 0.1% between kinematic wave and dynamic wave.

3.2.2 DDM

DDM is a 1D hydrologic-hydraulic model for simulating dual drainage in urban areas. (Nanía, León, & García, 2015) It consists of four modules: rainfall-runoff transformation, 1-D flow routing on a street network, inlet interception and sewer routing with SWMM engine.

The overland module concept in DDM is very similar to the one in SWMM. DDM uses kinematic wave instead of dynamic wave in SWMM. The main difference in overland model method is discussed in Section 3.2.3. The street module solves full 1-D open channel continuity and momentum equations by finite volume shock-capturing scheme. Part of the street flow is releasing outside watershed at outfalls. Part of the street flow is discharging into the next street intersection by gravitation. Other street flows are intercepted by inlets as the third module in DDM. The volume of flow intercepted is calculated based HEC-22 according to the inlet type. There are four inlet types in DDM: grate, curb-opening, slotted and combination inlets. After water enters the sewer system, DDM calls SWMM as its fourth module for sewer routing. If a sewer node is flooded, the overflow will be discharged back to its corresponding street through the inlet. This overflow will be routed in the street module again in the next time step.

The connection between each module is shown in Figure 10. One catchment could have a couple of discharging streets, and one street could have several input catchments. This n to n relation also works between streets and inlets. However, each inlet has its own and only one corresponding sewer, while one sewer may have several inlets.

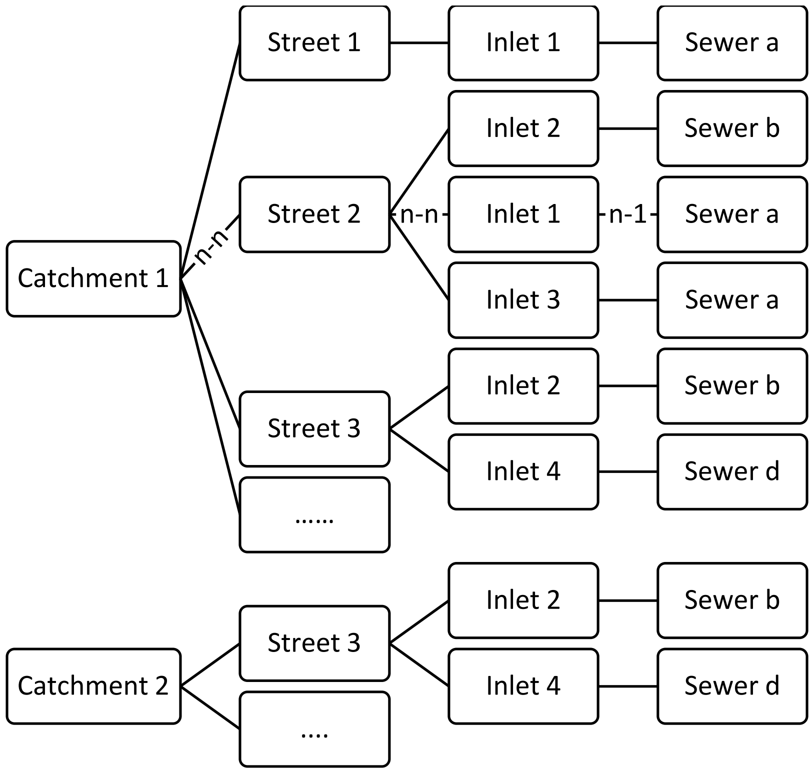


Figure 10 n-n and n-1 relationship for connections between DDM modules

3.2.3 Model Difference Highlight

3.2.3.1 Subdividing

Subdividing is the key difference in hydrological module between DDM and SWMM. In DDM, every plane is a part of the catchment linked to a surrounding street. Overland runoff is introduced uniformly distributed in the streets surrounding the blocks. (Nanía, León, & García, 2015) Given the same catchment properties, DDM automatically divides each catchment into smaller planes with different width and sums up all plane outflows as the overall runoff, while SWMM utilized one width in each catchment to calculate one overall runoff.

Subdividing would cause discrepancies in overland flow result, as higher peak, lower falling limb and less total volume. The reason is explained in two parts. Firstly, subdividing in DDM increases catchment width. The water would flow faster and less constricted on the catchment with long width. It would result in less infiltration and earlier peak in total runoff. (Rossman, 2015) Secondly, subdividing DDM results in shorter flow path length.

The flow time on each short plane decrease and the flow speed increase. These planes would store less water on-site and have shorter flow time. Both effects contribute to higher peak, lower falling limb and less total volume in DDM overland runoff.

3.2.3.2 Disconnecting

A summary of model steps for DDM and SWMM is shown in Figure 11. Street module helps DDM and SWMM to disconnect overland flow from sewer. The additional inlet interception module in DDM restricts this disconnecting interaction between surface and sewer system.

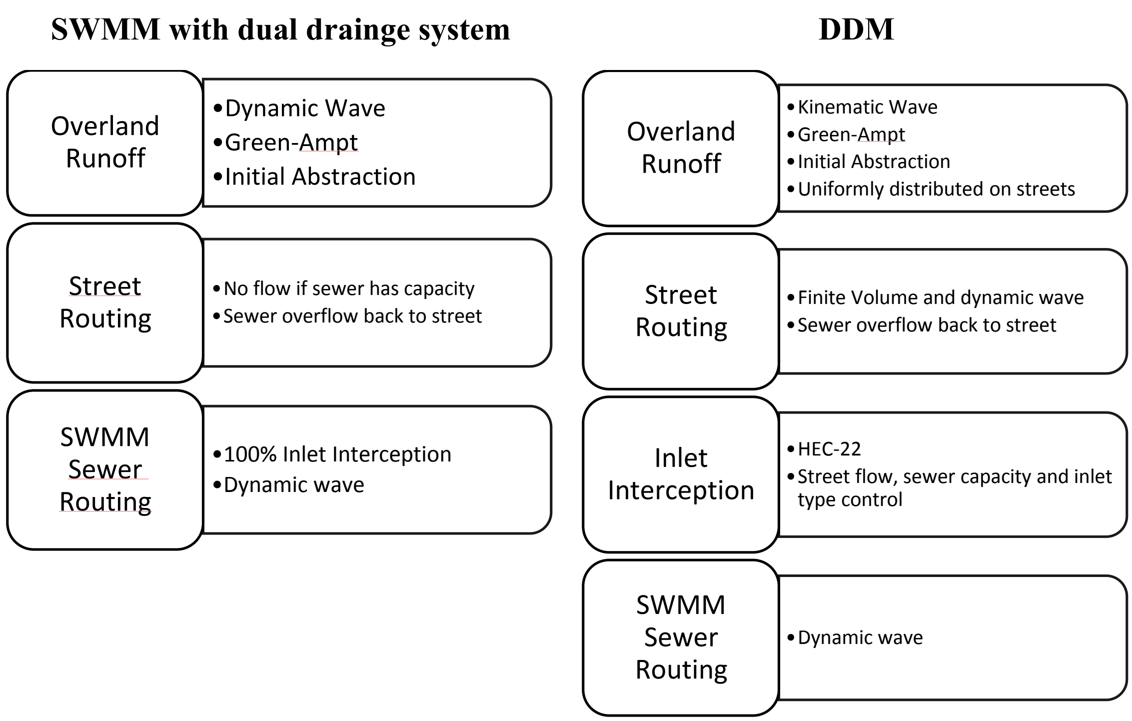


Figure 11 Model steps for SWMM (left) and DDM (right)

Adding street module could eliminate the error from the virtual pond assumption in traditional SWMM. Original SWMM assumes a hypothetical pond on top of each manhole to store overflowed sewer discharge. The virtually stored water will be discharged slowly back to the sewer system later by pressure. This virtual pond could be unreasonably large during extreme storms. Through adding street network, flooding sewer could now flow on streets and enter the sewer system at downstream.

Considering inlet interception in DDM restricts the interaction between underground sewer system and surface flow. SWMM assumes 100% inlet interception. Runoff on the surface would all discharge into the sewer system as long as it reaches the sewer manhole and sewer still has capacity. In other words, there will be no flow on the street until the parallel sewer pipe is full. Oppositely, DDM allows street flow regardless of sewer capacity.

DDM would calculate the inlet interception rate based on street flow, sewer capacity and inlet type by HEC-22. This helps to explain flooding in a low elevation street with large sewer pipes underneath and flooding in some street during minor low-intensity storms. The water captured by the inlets in DDM is controlled triply by street flow, sewer capacity and inlet interception rate.

3.3 Model Comparison Criteria

In this study, hydrograph and statistical errors were used to assess model difference between DDM and SWMM. Hydrograph worked as a visual comparison of time series data and a first overview of model performance. But it is hard to tell from a hydrograph how much the difference is and whether or not this difference is significant. To overcome these difficulties, statistical error were used to numerically quantify the model difference.

3.3.1 Hydrograph

A hydrograph is a time series graph showing the rate of flow versus time at a specific location. Visual comparison of hydrograph time series provides a quick and clear comprehensive assessment of model accuracy and difference. (Yen, 1981; Moriasi, et al., 2007; ASCE, 1993; Green & Stephenson, 1986) The disagreement in peak flow rate and overall shape fit are evident in hydrographs. Example hydrographs could be seen in Figure 16.

3.3.2 Statistic Error

The determination of peak flow rate and timing, flow volume and recession curve shape are important in watershed model assessment. (ASCE, 1993; Moriasi, et al., 2007) Equations used to quantify these differences are summarized below in Table 4. Although Nash Coefficient was originally developed for long-term river flow forecasting (Nash &

Sutcliffe, 1970), it is one of the widely used statistical analysis in hydrological study. So it was also included in Table 4.

Table 4 Criteria for model comparison (Green & Stephenson, 1986; Yen, 1981)

No.	Criterion	Equation	Remarks
1	Model efficiency	$R^2 = \frac{F_0^2 - F^2}{F_0^2}$ Where: $F^2 = \sum_{i=1}^{n} [q_0(t) - q_s(t)]_i^2$ $F_0^2 = \sum_{i=1}^{n} [q_0(t) - \bar{q}]_i^2$	Dimensionless; Nash Coefficient
2	Normalized objective function	$P = \frac{1}{\bar{q}}\left(\frac{F^2}{n}\right)^{\frac{1}{2}}$	Dimensionless; Coefficient of variance between models
3	Percent error in peak	$PEP = \frac{q_{ps} - q_{po}}{q_{po}} \times 100$	Dimensionless
4	Percent error in volume	$PEV = \frac{V_s - V_0}{V_0} \times 100$	Dimensionless
5	Percent error in peaking time	$PET = \frac{\overline{q_s} - \overline{q_0}}{\bar{q}_0} \times 100$	Dimensionless

3.4 Sensitivity Analysis

This sensitivity analysis aims to determine to what extent DDM is sensitive to GI. It was conducted on overland runoff during 2-year 60-minute storm, because GI is most effective to reduce overland runoff under frequent storms.

Decision variables included catchment characters and soil hydraulic properties, representing GI usage and behavior. Their values and ranges are shown in Table 5.

The sensitivity analysis was conducted under five scenarios. The first three aimed to compare the potential of GI under different John Street sewer conditions, while the latter two aimed to compare it under different John Street catchment conditions. All five scenarios are listed below, with a short explanation on their characteristics.

- Original John Street With Small pipes

Original John Street were covered by local soil with around 50 percent impervious. It was a flood prone area with sewer pipe diameter less than 30 inch.

- Retrofit John Street

Retrofit John Street improved its pipeline system to deal with the flooding problem. Now the main sewer pipe diameters are up to 60 inch.

- Retrofit John Street with GI

Engineered soil with better hydraulic conductivity and high infiltration rate was installed on top of retrofit John Street Model to test the influence from GI.

- Predevelopment

All catchments in John Street Watershed were assigned 5 percent impervious to represent predevelopment condition.

- Urbanization

All catchments in John Street Watershed were assigned 95 percent impervious to represent urbanization condition.

Table 5 Decision variables for sensitivity analysis

Decision Variables	Lower Bound	Model Baseline	Upper Bound
Imperviousness (%)	5	Current Condition	96
Depression Storage (mm)	5	12.7	20
Pervious Slope (%)	0.1	0.9	3
Effective Saturation (%)	29.8	31.3	31.8
Porosity	0.42	0.501	0.582
Suction Head (m)	0.0292	0.1668	0.9539
Hydraulic Conductivity (mm/h)	1.34	2.35	3.49
Manning's n	0.015	0.15	0.2

Tornado Plot and Unit Change Graph were used to interpolate results, considering the uncertainty in both variable value and range. Each variable in these graphs was used as an uncertain value between its lower and upper bound, while all other variables were held at its baseline value. The Tornado plot shows the result change from each variable, while the Unit Change Graph shows the fraction of result change over the uncertain variable range. Top bars in Tornado Plot and higher bars in Unit Change Graph represent higher sensitivity.

Example Tornado Plot and Unit Change Graph could been seen in Figure 25 and Figure 26.

CHAPTER 4 IMPLEMENTATION

Chapter 4 introduces the tools and models used in this study. Dual drainage system of John Street Watershed was built in both SWMM and DDM in such a way that the parameters describing the same area of different models are equivalent. A GIS Toolbox including several python scripts was used to generate input files from GIS for models. User Interfaces and operation window for DDM and SWMM were also presented.

4.1 GIS Toolbox

John Street Watershed layout in GIS consists blocks, streets, manholes, inlets and sewer pipes, as shown in Figure 6. A GIS Toolbox was built to generate data from GIS to DDM and SWMM input files. Data and corresponding process are summarized in Figure 12. One python script was used to generate the relationship between nodes and lines. Another python script was used to export data from GIS to input files like SWMM INP file and DDM CSV files. Data requirement and format for input files are summarized in Appendix A. This tool could save researchers a lot time and effort in model setup process with some modification to the target watershed.

4.2 DDM

Dual drainage system in John Street Watershed was built in DDM, including 26 blocks, 76 streets, 66 inlets, 68 manholes and 67 sewer conduits. There are three street outfalls and one sewer outfall. The connections between sewer and streets are shown in Figure 13. Upper links denote streets; Lower links denote sewer pipes, and circles represent sewer nodes. The layout of watershed is same as the one in SWMM, as shown in Figure 15.
DDM stores catchments, streets and inlets data in several CSV files. It uses SWMM INP file for sewer system data. DDM reads these input files only one time. It then runs and writes outputs in a couple of text files at every model time step. All inputs and outputs files in DDM are explained in Appendix A. A running window of DDM is shown in Figure 14.

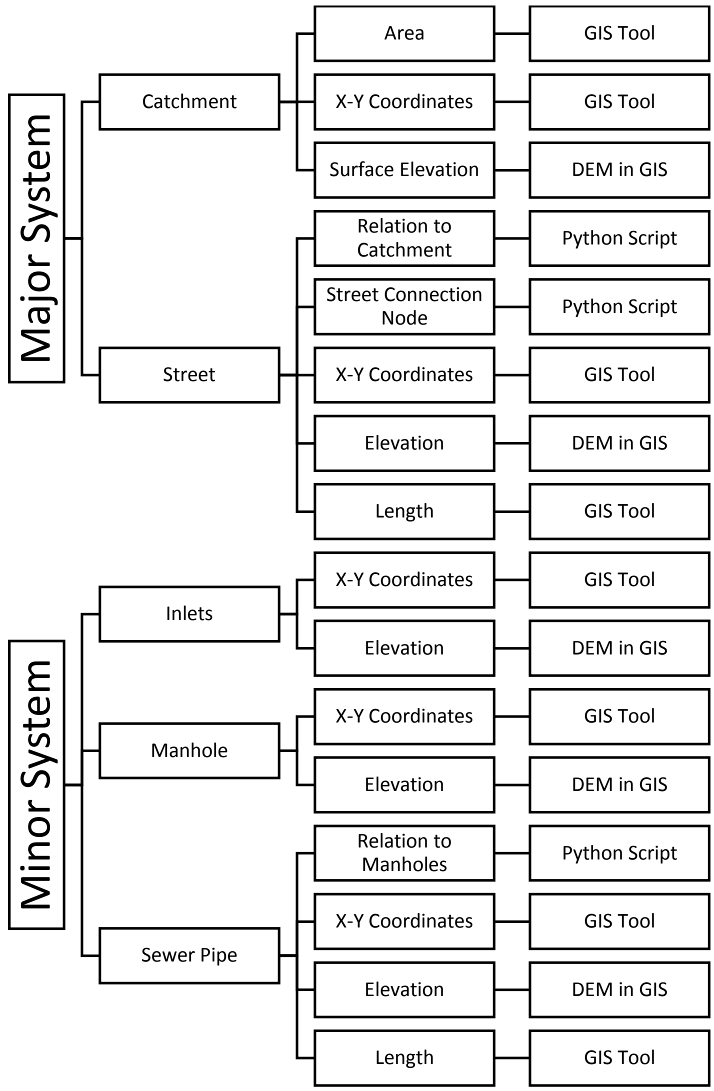


Figure 12 Target data and corresponding generation method in GIS for John Street Watershed

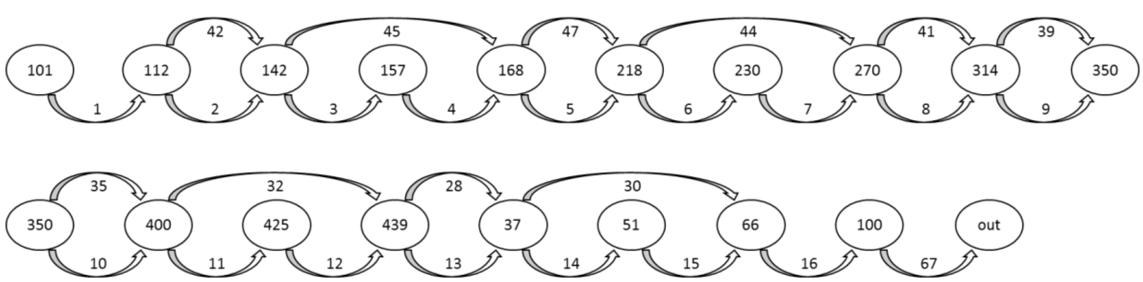


Figure 13 Main sewer and street network in DDM. Upper links denote streets, lower links denote sewer pipes and circles represent sewer nodes

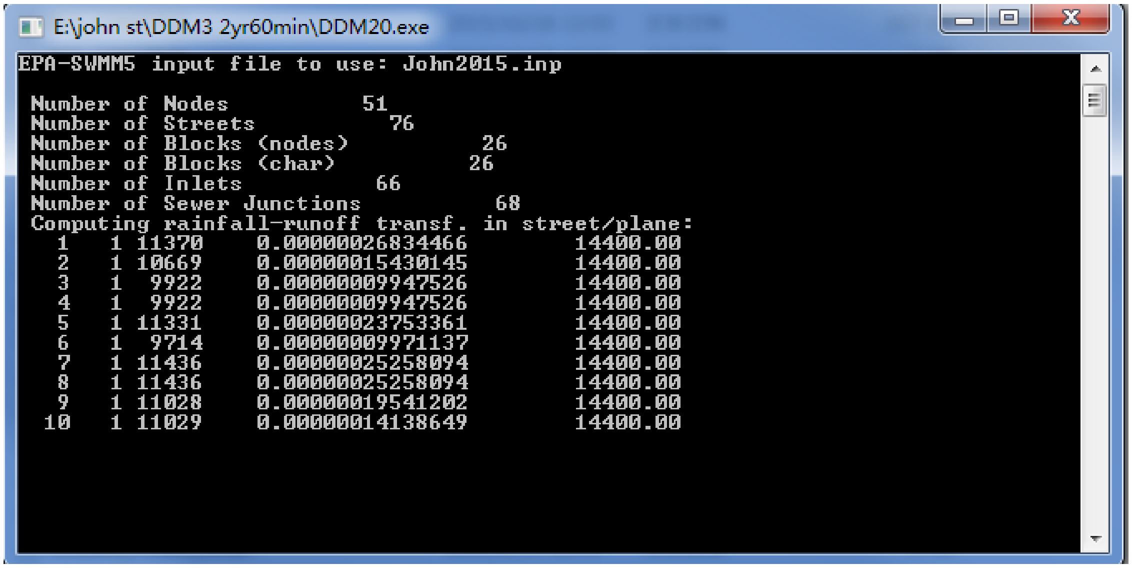


Figure 14 Example DDM running window for John Street Watershed

4.3 SWMM with Dual Drainage

SWMM was used to model dual drainage system of John Street Watershed in such a way that the parameters describing the areas of the different models are equivalent. It also includes 26 blocks, 76 streets, 66 inlets, 68 manholes and 67 sewer conduits. There are three street outfalls and one sewer outfall. The layout for John Street Watershed with notation of blocks is shown in Figure 15.

Two types of SWMM model were built to test the influence from outlet assignment for overland flow. The first one, SWMM connecting streets, joined catchment outflow to the highest elevation street node in that catchment, while the other, SWMM connecting sewer, linked overland outflow directly to the sewer system.

Most input data are same in DDM and SWMM, but there are still some minor data losses due to model capacity. For example, DDM accounts for different slope in pervious and impervious surface, while SWMM used the same value. SWMM could allocate impervious area with no depression storage, but DDM could not. Furthermore, kinematic wave is the only default setting in DDM for overland flow, while SWMM is limited to dynamic wave for dual drainage modeling. These differences were reduced as small as possible when building models.

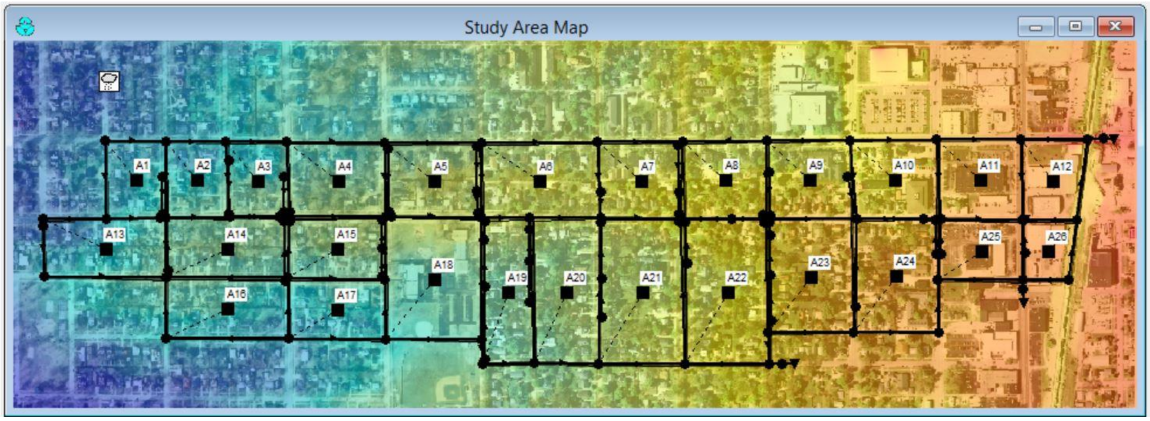


Figure 15 SWMM user interface with catchments, street network and sewer system (background image from IDOT (2014); surface elevation from ILHMP (2014), blue represents higher elevation and red represents lower elevation)

CHAPTER 5 RESULTS

In Chapter 5, three models introduced in Chapter 4, as DDM, SWMM connecting sewer and SWMM connecting street, were tested under four rain scenarios at John Street Watershed, Champaign IL. Four rain storms, 2-year 60-minute rain, 10-year 60-minute rain, 50-year 60-minute rain and 100-year 60-minute rain, were adopted from Huff distribution. The results were interpreted independently in terms of overland flow, street flow and sewer flow. The difference within models and between models were illustrated by hydrographs and statistical errors. In addition, a sensitivity analysis examined the potential for DDM's application on GIs.

5.1 Overland Runoff

In Section 5.1, both total and individual catchment overland runoff from DDM and SWMM were compared under four rain storms. The analysis of total overland runoff aims to examine the impact of model method difference, while the analysis of single catchment overland runoff aims to examine the model reaction to percent impervious. We expect to get higher peak, lower falling limb and less total volume in DDM total overland runoff than SWMM. We also expect to get more overland runoff from high impervious catchment.

5.1.1 Total Overland Flow

Total overland flow from DDM and SWMM were compared under four rain events, as shown by the runoff hydrograph in Figure 16 in conjunction with the rainfall intensity time series. Table 6 provides quantitative overland runoff and Table 7 provides percent error between models. SWMM connecting sewer and SWMM connecting streets showed identical overland runoff, since they shared the same overland character and the same model engine. They were combined and denoted as SWMM in Figure 16, Table 6 and Table 7.

2-year 60-minute rain is minor storm, so distinct rainfall reduction and small overland runoff are expected in both SWMM and DDM. 50-year and 100-year 60-minute rain events are major storms, so limited rainfall reduction and more overland runoff are expected for both models. 10-year 60-minute rain may show results with both characteristics of frequent and rare event. Results are illustrated in three aspects, as model performance, difference between DDM and SWMM, as well as DDM's reaction to different storms.

First of all, DDM and SWMM were both successfully transferring rainfall to overland flow. Figure 16 displays reduced and delayed total overland runoff in both models compared to rainfall time series. In Table 6, total overland runoff was reduced to less than 89% of total rainfall volume because of onsite soil infiltration. The time to peak total overland flow was delayed in both models, but only a little, because of the limited storage capacity for silt loam. In addition, major high intensity storm resulted in more total overland runoff volume, more peak runoff and less time to peak in both models, as shown in Table 6.

Secondly, DDM was more conservative than SWMM in estimation of overland flow peak and total volume. Table 6 displays higher peak flow and less total runoff volume in DDM compared to SWMM. Although the higher peak flow of DDM would cause a small amount of increase in total runoff volume, the lower falling limb in DDM lasted much longer and finally resulted in less total runoff volume, as illustrated by Figure 16. Another finding in Table 7 is that the Nash Coefficients were all larger than 0.9, which suggests good overall fit between hydrographs.

Thirdly, DDM demonstrated the closest fit to SWMM during major storm. The Nash Coefficient and Coefficient of Variance between models were not varying significantly under different storms, which suggests that the fitness of model is not sensitive to rain intensity. However, the volume error between DDM and SWMM was reduced from -9.35 to -1.41 % error and the peak flow error was increased from 7.25 to 27.27 %, comparing minor storm to major storm. DDM generated the closest total volume and hydrograph shape as SWMM, while the peak flow is much higher for conservative design criteria during a major high intensity storm.

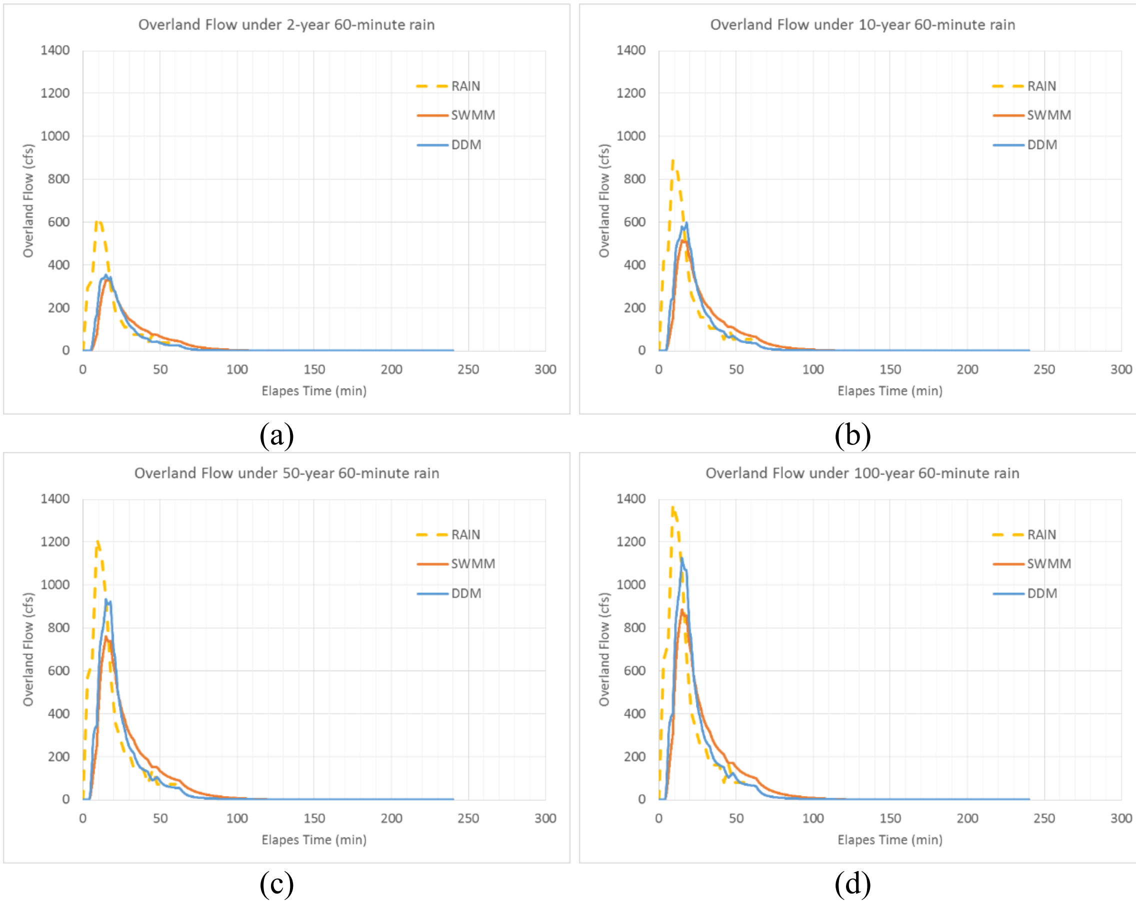


Figure 16 Rainfall to overland flow transformation in DDM and SWMM under (a) 2-year 60-minute rain (b) 10-year 60-minute rain (c) 50-year 60-minute rain (d) 100-year 60-minute rain. (SWMM connecting sewer and SWMM connecting streets showed identical overland flow, which were combined and denoted as SWMM)

Table 6 Total overland runoff in DDM and SWMM under 2-year, 10-year, 50-year and 100-year 60-minute rain

Results\Rainfall	2-year 60-minute		10-year 60-minute		50-year 60-minute		100-year 60-minute	
	SWMM	DDM	SWMM	DDM	SWMM	DDM	SWMM	DDM
Rainfall (inch)	1.41	1.41	2	2	2.74	2.74	3.11	3.11
% Runoff	76.19	69.07	82.45	77.95	86.77	84.54	88.22	86.98
Overland Runoff (inch)	1.07	0.97	1.65	1.56	2.38	2.32	2.74	2.7
Peak Runoff (cfs)	331.58	355.6	515.23	598.53	759.8	933.11	885.74	1127.28
Time to Peak (s)	1080	900	900	1080	900	900	900	900
Mean Flow Rate (cfs)	34.95	31.68	53.64	50.72	77.35	75.36	89.26	88

Table 7 Total overland runoff difference between DDM and SWMM under 2-year, 10-year, 50-year and 100-year 60-minute rain

Model Fitness\Rainfall	2-year 60-minute	10-year 60-minute	50-year 60-minute	100-year 60-minute
Overland Runoff error %	-9.35	-5.45	-2.58	-1.41
Peak Runoff error %	7.25	16.17	22.81	27.27
Time to Peak error %	-16.67	20	0	0
Mean Flow Rate error %	-9.35	-5.45	-2.58	-1.41
Nash Coefficient	0.92	0.94	0.93	0.93
Coefficient of Variance (CV) between models	0.57	0.53	0.56	0.58

5.1.2 Single Catchment Overland Flow

Overland runoff from urbanized and rural catchments were compared to test DDM's performance under different catchment properties. Urbanized catchment with higher percent imperviousness is expected to generate higher overland runoff compared to rural catchment. Catchment 4 and 11 have similar area as 5 acres and 4.6 acres. They are both located at the north side of John Street. The plan views are shown in Figure 17. Catchment 4 consists of low or median intensity residential houses with 44 percent impervious, while catchment 11 consists of more developed and urbanized land with 91 percent impervious. They represent rural area and urban area accordingly.

(a) Catchment 4 (5 acre, 44 percent impervious)

(b) Catchment 11 (4.6 acre,91 percent impervious)

Figure 17 Catchment 4 and Catchment 11 plan view in John Street Watershed

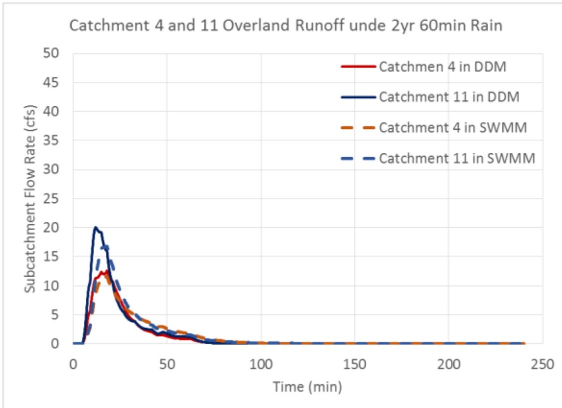
Overland flow from both catchments 4 and 11 had higher peak, lower falling limb and less total volume in DDM, similar to total overland flow, as shown in Figure 18. In addition, overland flow from both catchments 4 and 11 increased with rain intensity, also similar to total overland flow.

More overland flow was generated from urbanized catchment 11 than rural catchment 4, as shown by the area under the curve in Figure 18, same as expected. Figure 18 also implies that the peak flow differences between SWMM and DDM during different storms are quite different. In urbanized catchment 11, the peak flow difference between models is close in all storms, while in rural catchment 4, this difference is smaller in minor low intensity storm and higher in major storm. This indicates that DDM shows close overland peak runoff to SWMM in urban area under all storms, although the difference is quite significant in rural area especially during rare event.

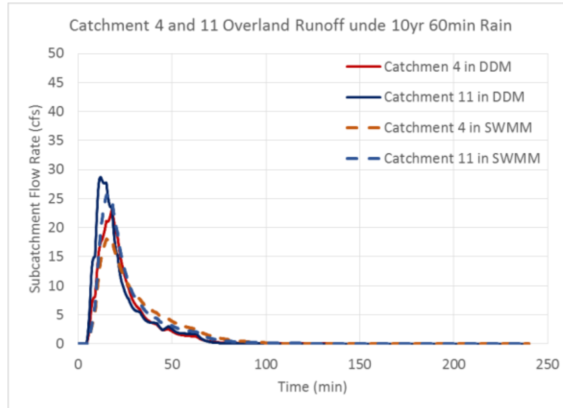
Table 8 presents the fitness of hydrographs between SWMM and DDM for catchment 4 and 11. In urbanized catchment 11, Nash Coefficient is higher and Coefficient Variance between models is lower in high intensity storms, which both indicate better fit. While in rural catchment 4, it is quite the opposite and the fitness is worse in high intensity storms. This indicates that DDM and SWMM generates closer hydrograph in high percent impervious area under major high intensity storm.

Table 8 Overland flow time series fitness between SWMM and DDM for Catchment 4 and 11 under 2-year, 10-year, 50-year and 100-year 60-minute rain

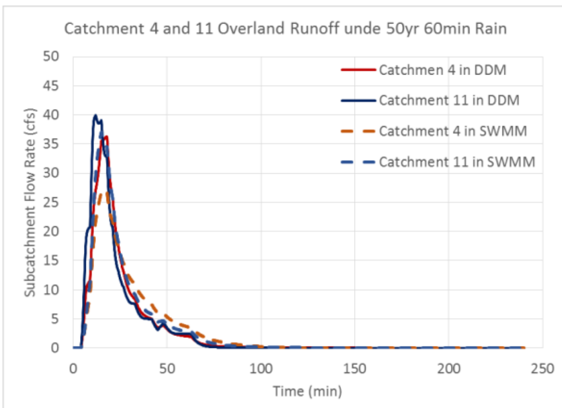
Rainfall	Model Fitness	Catchment 4	Catchment 11
2-year 60-minute	Nash Coefficient	-1.679	-5.953
	CV between models	0.557	1.011
10-year 60-minute	Nash Coefficient	-1.987	-3.891
	CV between models	0.59	0.873
50-year 60-minute	Nash Coefficient	-2.653	-2.711
	CV between models	0.66	0.776
100-year 60-minute	Nash Coefficient	-2.889	-2.396
	CV between models	0.686	0.748



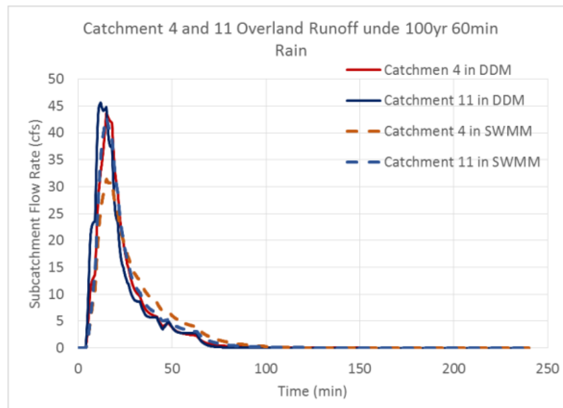
(a)



(b)



(c)



(d)

Figure 18 Overland runoff from Catchment 4 and 11 in DDM and SWMM under (a) 2-year 60-minute rain (b) 10-year 60-minute rain (c) 50-year 60-minute rain (d) 100-year 60-minute rain

5.2 Street Flow and Inlet Interception

To eliminate the influence of overland runoff difference to sewer flow error (Yen, 1981; Green & Stephenson, 1986), the following analysis used the same SWMM overland flow time series from Figure 16. All flow results would be only related to the hydraulic properties of street and sewer network, instead of hydrological catchment characters. In addition, only main street and sewer network were analyzed in the following Sections to study the flooding problem. Main streets are streets connected with parallel underground main sewer pipes, which have the largest amount of runoff.

In Section 5.2, street module and inlet interception module were analyzed with same SWMM overland flow time series under four storms. SWMM connecting streets joined catchment outflow to the highest elevation street node in that catchment, while SWMM connecting sewer linked overland outflow directly to the sewer system. All three models included major street network as dual drainage system.

5.2.1 Street Flow Depth

Main street flow depth in DDM under different storms were presented in Figure 19. DDM main street flow hydrograph shared similar shape like overland runoff, but with fatter tail and oscillating peak, comparing Figure 16 and Figure 19. The fatter tail accounted for the convergence of tributary overland runoff and the delayed flowing time on streets. The oscillating peak implied interaction between sewer and street.

The upstream and downstream street depth were compared in DDM. According to Figure 13, the street number from upstream to downstream is 42, 45, 47, 44, 41, 39, 35, 32, 28 and 30. Downstream streets 44 and 41 presented higher flow depth than upstream streets 42, 45 and 47, as shown in Figure 19. However, streets 39, 35, 32 28 and 30 showed decreasingly smaller flow depth than their upstream streets 44 and 41 in Figure 19. It was because street outfall, right downstream of street 30, was releasing water, which reduced the street flow depth. Main street depth was supposed to be higher at downstream than upstream in DDM if the watershed area was larger.

DDM showed street flow during both minor and major storm. The maximum street flow depth in DDM was 0.9-ft for 2-year 60-minute storm and 1.8-ft for 100-year 60-minute event, as shown in Figure 19. Both are higher than a regular curb height 0.5-ft. For a 2-year storm, little or no street flow is expected. DDM was overestimating street flow for minor low intensity storm. For a 100-year storm, flooding and high street depth were expected. 1.8-ft street depth was too high, but could still serve as a conservative flooding prediction.

In addition, only DDM was able to provide major street flow time series. SWMM connecting sewer showed no street flow, referring to street outflow in Figure 21. SWMM connecting streets had no main street flow but high minor street flow, which contributed to street outflow in Figure 21.

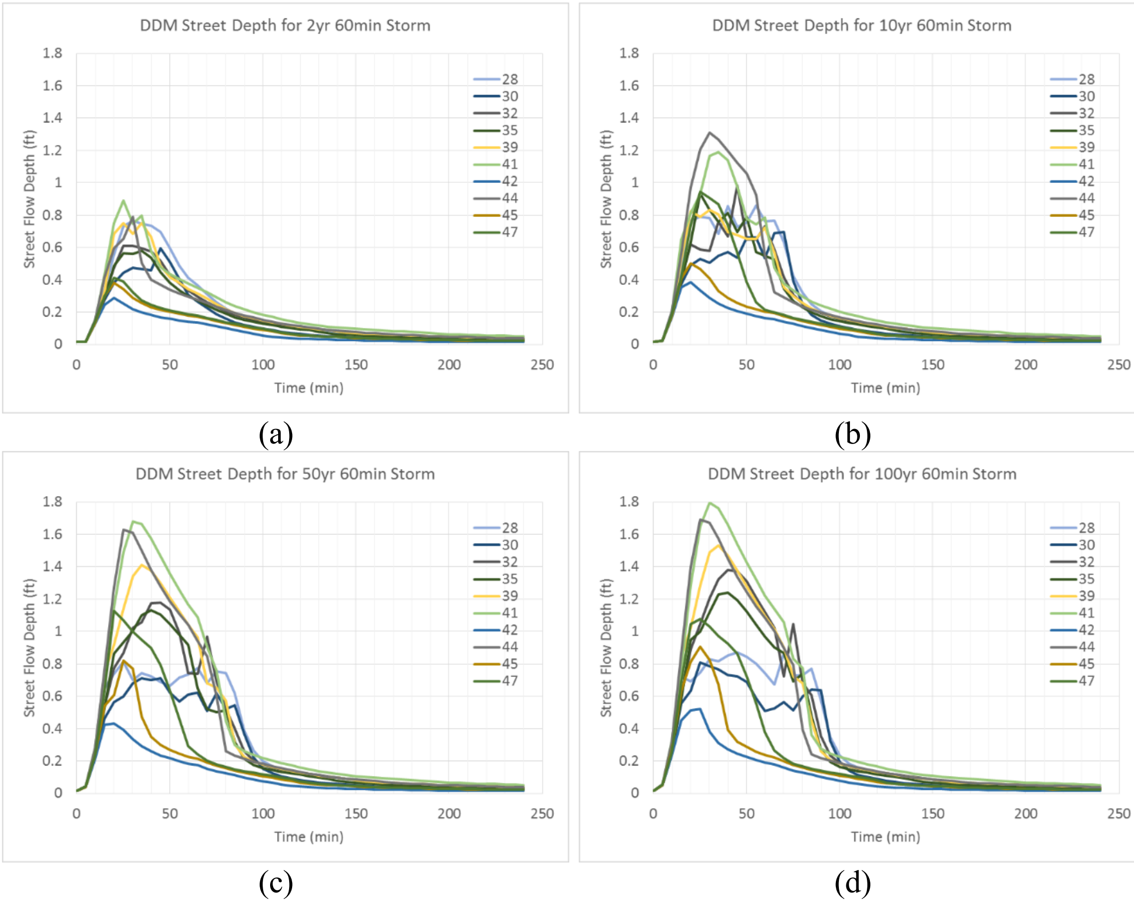


Figure 19 DDM main street network flow depth under (a) 2-year 60-minute rain (b) 10-year 60-minute rain (c) 50-year 60-minute rain (d) 100-year 60-minute rain. Legends represents street number, which follows the order 42, 45, 47, 44, 41, 39, 35, 32, 28 and 30 from upstream to downstream

5.2.2 Inlet Interception

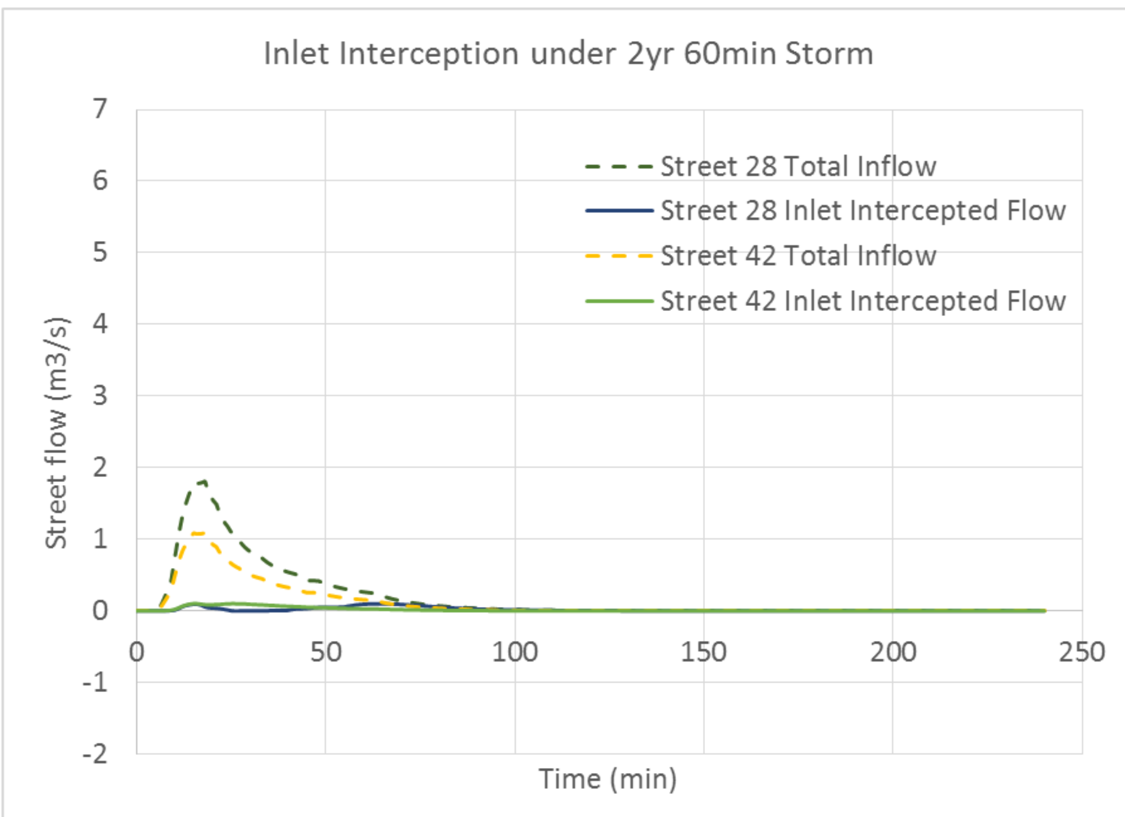
Inlet interception is the key module in DDM which directly determines how much water will enter the sewer network, although this amount of flow also depends on street flow and sewer capacity. Inlet interception is positive if street flow enters sewer and negative if sewer backflows to street. The breakdown of street flow mass balance is shown in the equation below.

$$Upstream\ total\ inflow = Street\ flow + Inlet\ interception + Street\ outflow$$

Figure 20 comprises upstream total inflow and inlet interception for street 28 and 42 under 2-year and 100-year storm. Street 42 is the first upstream major street, while street 28 is the second last downstream street. Not all street inflow would be intercepted by inlets in

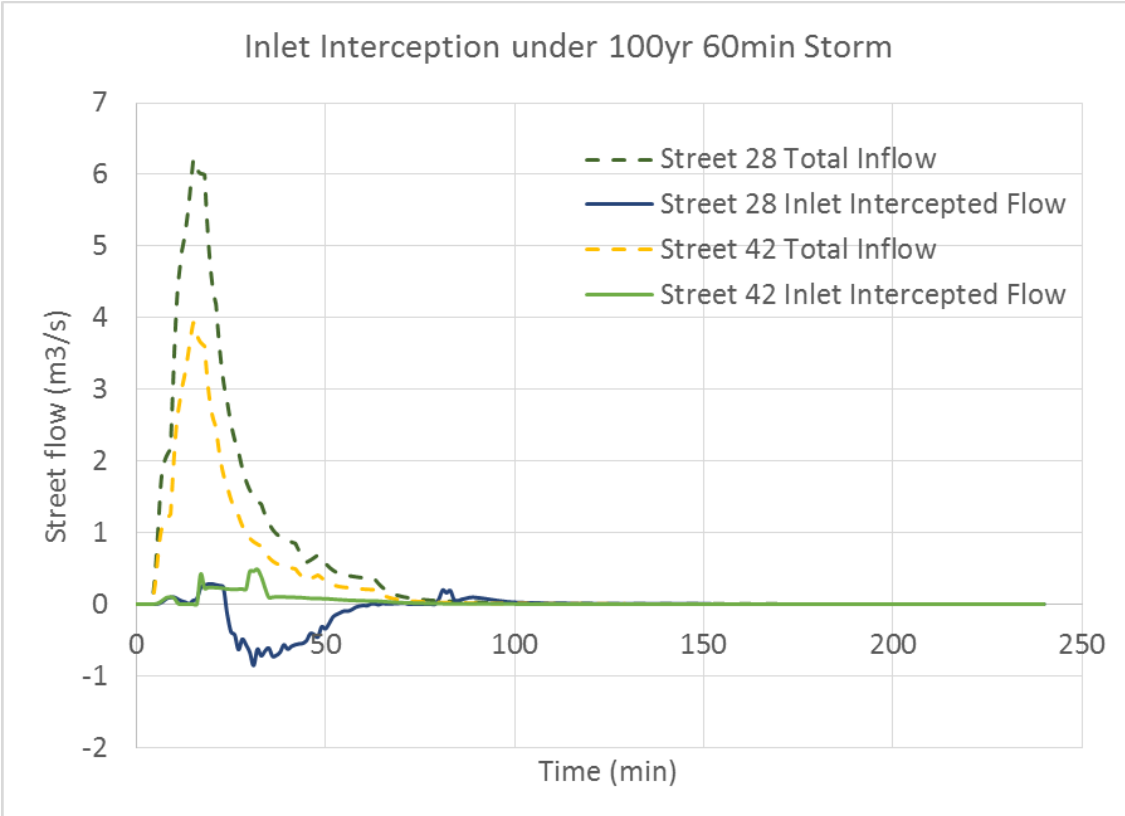
DDM, as illustrated by the smaller area under the inlet interception curves in Figure 20. The inlet type would restrict the amount of water entering, which could also explain the overestimation of street flow in DDM.

At upstream, inlet interception increased when there were more inflow, comparing street 42 under 2-yesr and 100-year storm. But at downstream, street 28 had smaller or even negative Inlet interception with higher inflow than upstream street 42. Because sewer had reached its capacity at downstream. No matter how large the inlet or inflow, there was no room available for more sewer input. In addition, sewer would even overflow back to street under major storms, as shown by the negative inlet interception of street 28 under 100-year storm in Figure 20. So inlet interception is sewer capacity control at downstream and inflow control at upstream in DDM.



(a)

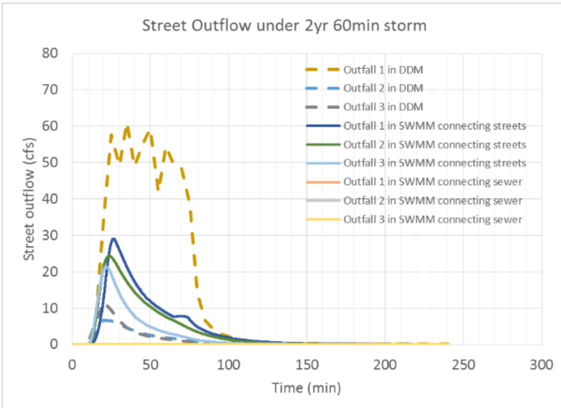
Figure 20 Street 28 and Street 42 inlet interception under (a) 2-year 60-minute rain (b) 100-year 60-minute rain



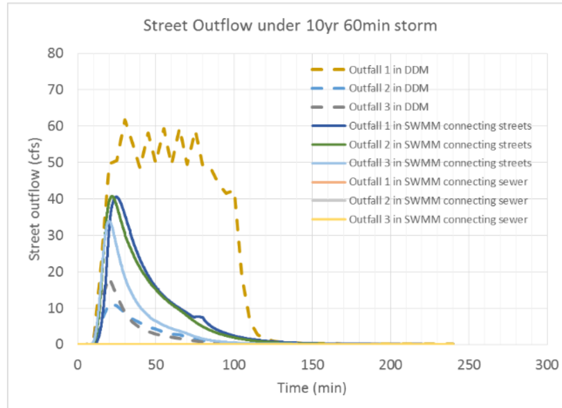
(b)
Figure 20 (cont.)

5.2.3 Street Outflow

Figure 21 plotted street outflow for DDM, SWMM connecting sewer and SWMM connecting streets under different storms. There are three street outlets, among which outfall 1 has the lowest surface elevation. SWMM connecting sewer had 0 street outflow in Figure 21, since 100% of street flow entered sewer system directly. SWMM connecting street had high outflow, although it all came from minor streets. DDM street outfall 1 showed large variance due to large routing step and sewer interaction. DDM street outflow 2 and 3 had much smaller flow compared to outflows in SWMM connecting sewer. This huge discrepancy between models makes the accuracy of street outflow in question, and it is hard to draw any conclusion without observatory data.



(a)



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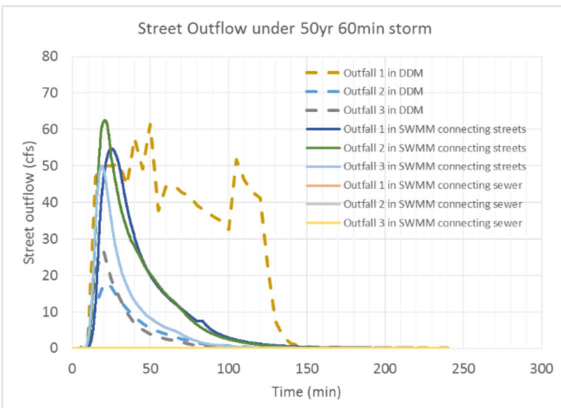

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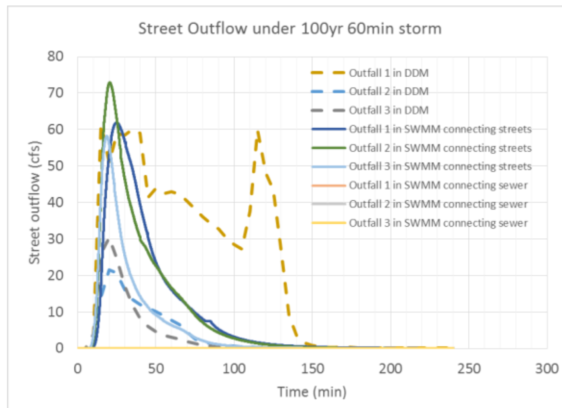


(d)

Figure 21 DDM street outflow under (a) 2-year 60-minute rain (b) 10-year 60-minute rain (c) 50-year 60-minute rain (d) 100-year 60-minute rain

5.3 Sewer Outflow

Sewer flow from DDM and SWMM were also compared with the same SWMM overland flow input under different storms from Figure 16. DDM called SWMM hydraulic sewer engine to model the sewer system. So the sewer outflow difference between models were only related to different sewer inflow.

In Table 9, DDM showed more sewer outflow in rare events and less in frequent events than SWMM. In Figure 22, SWMM connecting sewer always had the highest peak, but didn't last long. The peak flow from DDM increased much faster than SWMM models. It was also more delayed and retained in DDM than SWMM connecting sewer during rare event, which resulted in the highest total volume.

Taken together, there are less peak but long lasting sewer outflow in DDM model during rare event, when water entering sewer is limited. There are more peaked but fast reduced sewer outflow in SWMM connecting sewer model during rare event, when all overland runoff is entering sewer. Sewer outflow behaves quite different with different inlet interception rate.

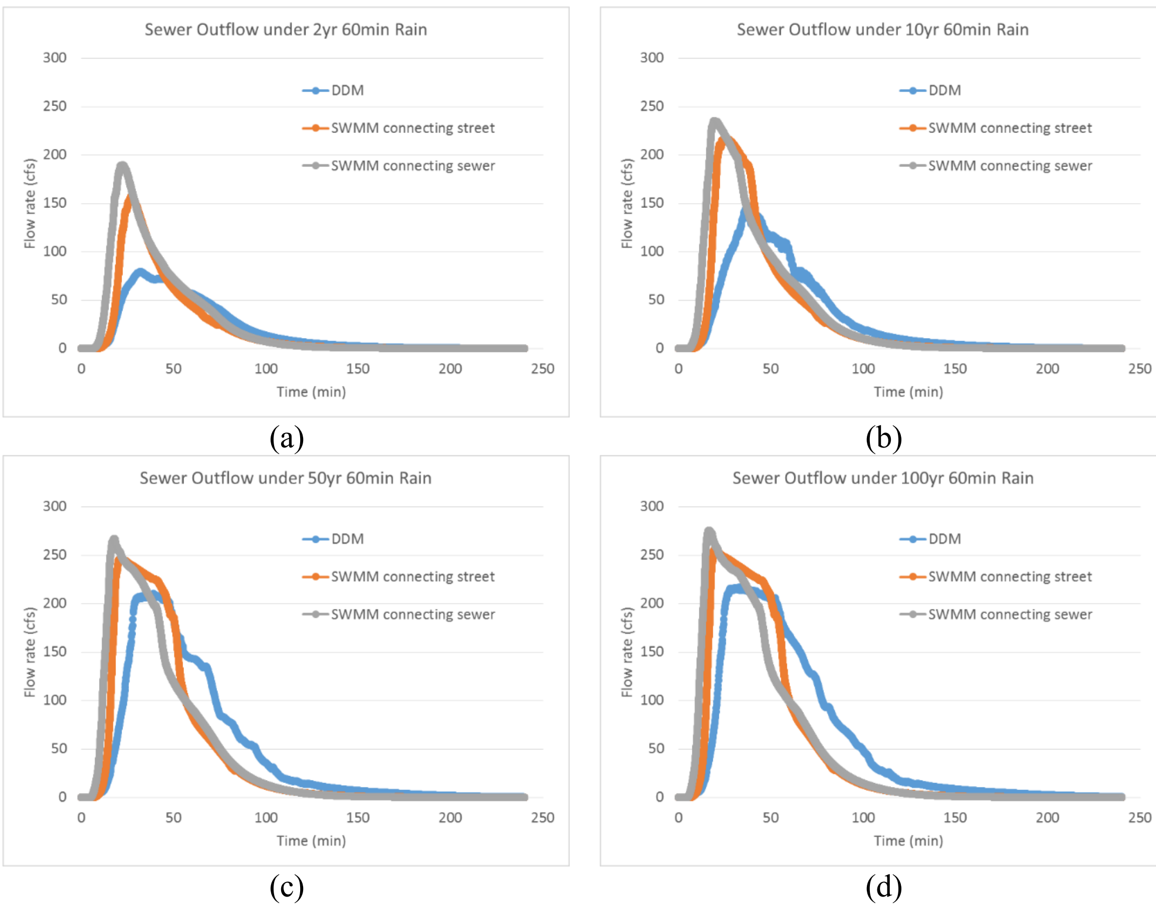


Figure 22 Sewer outflow in DDM, SWMM connecting street and SWMM connecting sewer under (a) 2-year 60-minute rain (b) 10-year 60-minute rain (c) 50-year 60-minute rain (d) 100-year 60-minute rain

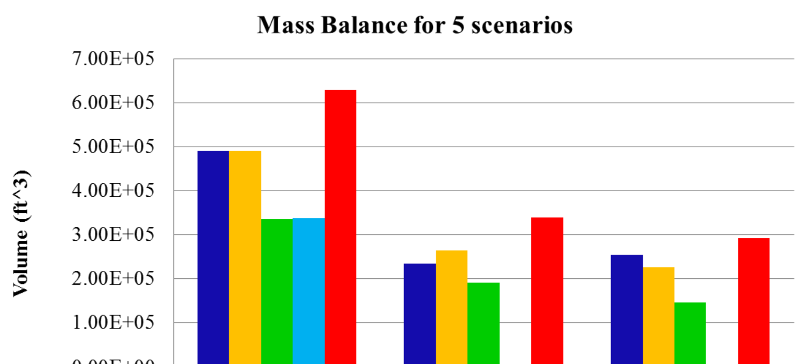
Table 9 Sewer total outflow under 2-year, 10-year, 50-year and 100-year 60-minute rain

Sewer Total Outflow\Rainfall	2-year 60-minute	10-year 60-minute	50-year 60-minute	100-year 60-minute
DDM	270823.6	436851.3	700717.9	809450.7
SWMM connecting street	303363.3	472985	650791	713195.8
SWMM connecting sewer	390377.6	533201.5	670773.6	721822.4

5.4 Sensitivity Analysis

A sensitivity analysis was conducted for DDM under five scenarios with 2-year rainfall to test its potential for GIs (GI) application.

Figure 23 presented the total volume of overland surface runoff, sewer flow and street flow. Each color represented one scenario, as described in Section 3.4. Urbanization scenario showed the largest amount of total runoff in red color, which indicates that high percent imperviousness would generate more runoff. The retrofit John Street with GI and predevelopment scenario had least two overland flow, because of low percent impervious and high soil infiltration capacity.



	Surface runoff (ft^3)	Sewer flow (ft^3)	Street outflow (ft^3)
Original John St With Small pipes	4.90E+05	2.35E+05	2.54E+05
Retrofit John St	4.90E+05	2.64E+05	2.25E+05
Retrofit John St with GI	3.35E+05	1.90E+05	1.45E+05
Predevelopment	3.38E+05		
Urbanization	6.29E+05	3.38E+05	2.92E+05

Figure 23 Surface runoff, sewer flow and street flow volume in DDM during 2-year 60-minute rainfall under 5 scenarios, as Original John Street with Small Pipes, Retrofit John Street, Retrofit John Street with GI, Predevelopment and Urbanization

Hydrographs for retrofit John Street with and without GI were shown in Figure 24. Retrofit John Street had obvious oscillating sewer flow, while retrofit John Street with GI didn't.

This oscillating was resulted from sewer and street interaction during flooding. It suggested that GI could reduce surface runoff. This effect was also supported by Figure 23 that retrofit John Street with GI had less surface runoff, less sewer flow and also less street outflow than the retrofit John Street.

Table 10 illustrated the flooding conditions in John Street Watershed under different scenarios. Original John Street with small pipe diameter had the worst sewer flooding, as 22 flooding nodes and 47 minutes of flooding. Retrofit John St had no flooded nodes. It indicated that larger sewer pipe size would allow for more sewer flow and relief the street overflowing.

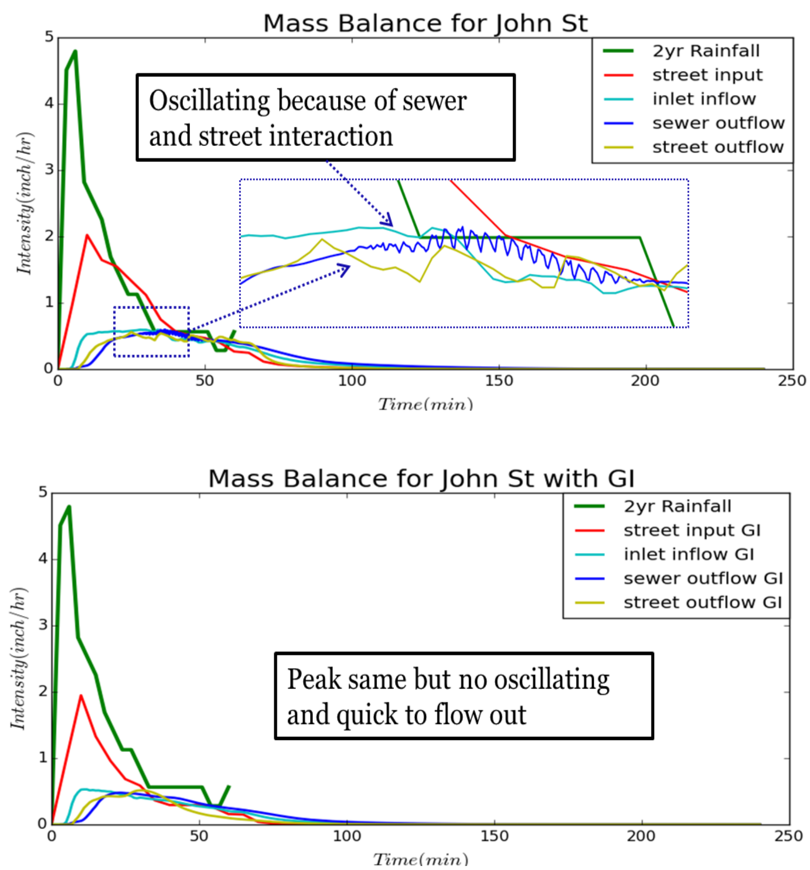


Figure 24 Hydrograph for Retrofit John Street Watershed with and without GI under 2-year 60-minute rain

Table 10 Flooding condition in DDM during 2-year 60-minute rain under 4 Scenarios, as Original John Street with Small Pipes, Retrofit John Street, Retrofit John Street with GI and Urbanization

Scenario	Flooded manhole (Num.)	Manholes flooded duration (minute)	Flooded street (Num.)
Original John St With Small pipes	22	47	5
Retrofit John St	0	0	4
Retrofit John St with GI	0	0	4
Urbanization	2	16.83	13

Figure 25 and Figure 26 are Tornado Plot and Unit Change Graph for sensitivity analysis. Percent imperviousness had biggest influence on total surface runoff volume, as shown by the top widest bar in Figure 25 and tallest bar in Figure 26. Unit change in percent imperviousness resulted in approximate 0.3 unit change in surface runoff. In addition, runoff was also sensitive to soil type parameters like suction head, depression storage, porosity and hydraulic conductivity, also indicated by wide bars in Figure 25 and tall bars in Figure 26.

From the results in sensitivity analysis, we could conclude that DDM is sensitive to GI by percent impervious and soil type under minor storm. The runoff from watershed would be least with low percent imperviousness, large sewer pipe diameters and better soil hydraulic properties.

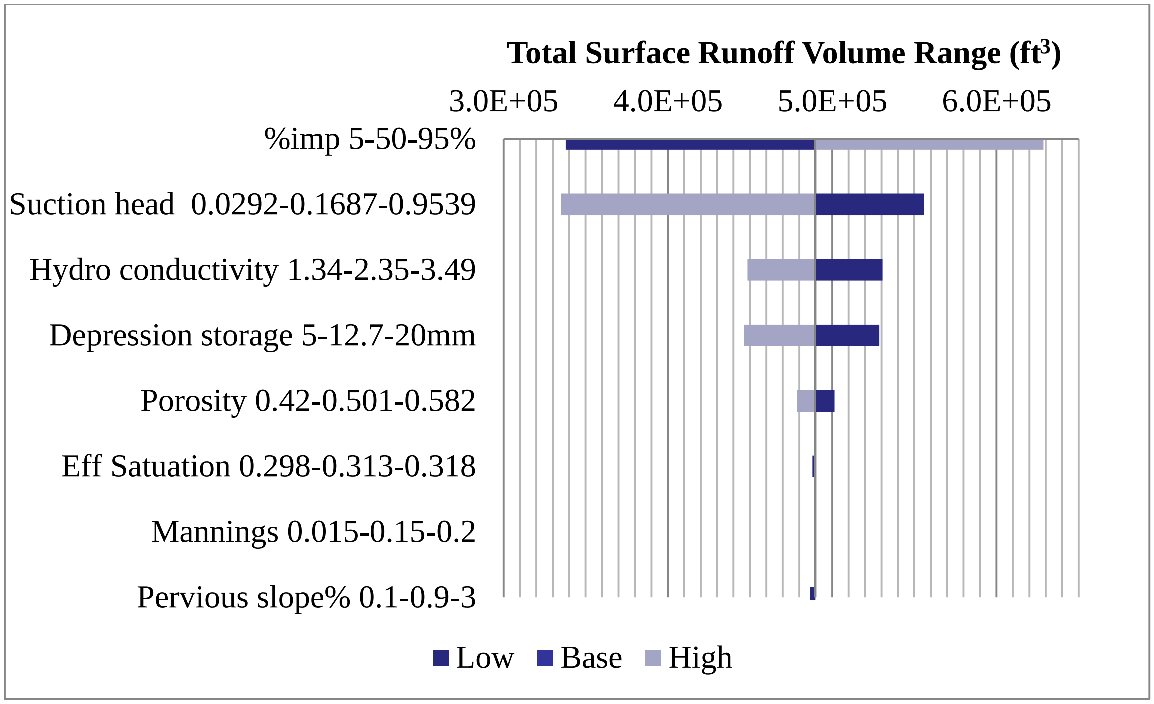


Figure 25 Tornado Plot for total surface runoff volume sensitivity analysis

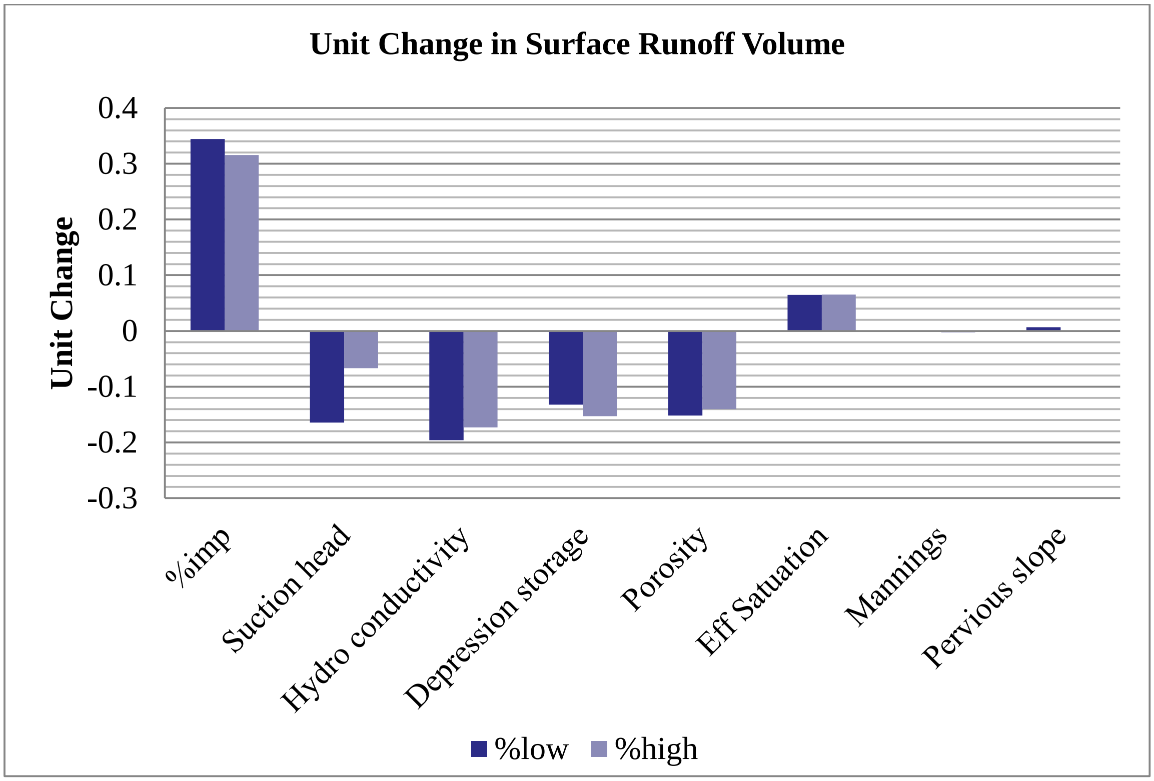


Figure 26 Unit Change Graph for total surface runoff volume sensitivity analysis

CHAPTER 6 DISCUSSION

This study focused on modeling dual drainage system in John St Watershed, Champaign IL by DDM during different storms. The model performance of DDM was compared to two dual drainage systems in SWMM, represented by SWMM connecting sewer and SWMM connecting street. A sensitivity analysis was conducted to test DDM's applicability to GI. In Chapter 6, the potential of DDM is examined in four aspects, DDM model method advantage, reaction to storms, effects within DDM and GI application. DDM demonstrated high potential for major storm modeling and GI application.

6.1 DDM Model Method Advantage

DDM was more conservative than SWMM in estimation of overland flow peak and total volume. It could provide detailed major street system flow and depth time series, while SWMM could not. These advantages of DDM could be attributed to the model methods, accordingly as subdividing effect and inlet interception.

6.1.1 Catchment Subdividing Effect

Subdividing effect, as explained in Section 3.2.3, is the key difference in hydrological module between DDM and SWMM. It is expected to result in higher peak and less total overland runoff volume, which is conservative and favorable in flooding assessment during major storms. Results in Section 5.1.1 accorded with this hypothesis.

Although we could not conclude the accuracy without observe data, subdividing effect still have several advantages. It takes into account different flow directions in overland flow, which is a prerequisite for detailed street flow analysis. It could reduce the error from arbitrary assignment of overland flow width in SWMM by automatic calculation. In addition, it could save researchers a lot of time and energy from measuring flow width, especially in a large area.

In summary, DDM overland flow module is preferable with subdividing and width effect when researchers could accept a conservative estimation for overland flow, and when researchers want reasonable overland flow width for large watershed area quickly.

6.1.2 Inlet Interception

DDM and SWMM could both model major street system. However, the amount of runoff staying on street or entering sewer is quite different due to inlet interception rate. SWMM assumes 100% inlet interception, while in DDM it is controlled mainly by water input and inlet type under minor storm at upstream nodes and by sewer capacity under major storm at downstream nodes.

Because of the restricted inlet interception rate, DDM generated high street outflow during major high-intensity storms. DDM also showed high main street flow depth during major storms, indicating flooding on streets. In contrast, SWMM could not analyze major streets flow with parallel sewer pipes, which are often the flood-prone area during major storms. It only allows sewer overflow on streets, but ignores possible street flow because of 100% inlet interception. Therefore, DDM would definitely be a better choice from the perspective of studying flooding in major system during major storms.

6.2 DDM under Different Storms

Overland flow, street flow and sewer flow results from DDMs were examined under minor and major storms. Results during minor storm was not very encouraging for DDM, while results during major storm indicated high potential for DDM. Dual drainage system aims to assess flooding on major system during major storms, so results during major storm are our main focus of study.

6.2.1 Minor Storm

During a 2-year frequent event, DDM overland flow had higher peak, shorter tail and less total volume than that in SWMM. With the same overland flow input, DDM overestimated street flow and in turn underestimated sewer flow compared to SWMM. The street depth is up to 0.9-ft in DDM during a 2-year storm, which is higher than a regular curb height 0.5-ft. There should not be that much street flow during minor storm, not to say any street flooding. This result was not encouraging for frequent rain event application. But DDM could still serve as an alert for flood prone area, since SWMM could not show any street flow as long as sewer is not full.

In addition, this study was conducted at a small watershed with median percent impervious. DDM may have better results under larger area, as discussed in Section 6.3.

6.2.2 Major Storm

During a 100-year storm, results from DDM, SWMM connecting streets and SWMM connecting sewer were examined in three aspects, overland flow, street flow and sewer flow. Overland flow in DDM had higher peak runoff but close total volume as that in SWMM. With same overland flow input, street flow in DDM was higher than SWMM, while sewer flow had close total volume with less peak flow and longer peak time. These results have important implications for future application of DDM in major storms.

First of all, for design criteria based on peak flow reduction, DDM would be a more conservative approach than SWMM while keeping similar total runoff volume. The total overland runoff error was only 1.41% between two models during 100-year storm in Table 7. DDM with subdividing effect presented more peak overland flow in Figure 16. The peak flow error was the highest 27% during 100-year storm as shown in Table 7. The higher peak in DDM may increase the design budget, but would also greatly reduce the flood risk, which is the aim of this study.

Secondly, DDM could quantify street flow on major streets, while SWMM could only assess sewer overflow on streets. DDM displayed high street depth and more street flow during major storms. The maximum street depth was 1.8-ft for a 100-year 60min storm in DDM, although it was more than expected. DDM accounted for inlet interception rate and sewer capacity, which would limit the street flow entering the sewer system even if the sewer system has the capacity. It was also a conservative estimation on the worst scenario and better for flooding risk assessment. Conversely, street depth was kept 0 in SWMM unless there was sewer overflow, which in this study was still very small. Street flow in SWMM only accounted for sewer capacity. It would be hard to estimate potential street flooding problems due to street alignment and inlet clogging in SWMM.

Thirdly, DDM could identify detailed flooding locations. Figure 10 and Figure 13 presented the connection of streets, inlets, manholes and sewer pipes in DDM. DDM also calculated the percentage of street flow into certain inlet and manhole. These two factors made the identification of flooding in detailed location and reason possible. SWMM could also locate the flooding manhole and pressurized sewer pipe. However, it may underestimate street flooding by only allowing sewer outflow on major streets and overestimate the number of flooding manholes by 100% inlet interception rate.

The main aim for dual drainage system design is to identify the major surface system flooding. In general, DDM could look insight into street flooding condition during rare event, with reasonable estimation of total overland flow and sewer flow. It is also more conservative in flooding estimation and risk assessment.

6.3 Effects within DDM

This Section aims to discuss some factors within DDM itself, which may either lead to more accurate results or cause discrepancy. Three factors are discussed, as percent impervious effect, downstream effect and model size influence.

6.3.1 Imperviousness Effect

Catchment properties such as percent impervious will directly influence overland flow volume, which in turn changes street flow and sewer flow. DDM generates the closest result as SWMM in high percent impervious area under major storm, as shown in Catchment 11 of Table 8 and Figure 18. This is a good suggestion for DDM to apply for major storms in urban area.

However, DDM is not sensitive to percent imperviousness during major storms. When it is more than 50-year storm, the general shape of the overland hydro graph from two different percent impervious area became closer in DDM, as shown by Catchment 4 and 11 in Figure 18. This shape difference was much larger in SWMM. It implies DDM may not be able to detect the influence from GI coverage during major storms, although the effect of GI is already limited during major storms.

6.3.2 Downstream Effect

Flooding mainly occurred at downstream of the watershed, and DDM generated reasonable downstream results. Figure 20 showed more street inflow and sewer outflow in DDM at downstream street 28 than upstream street. Downstream streets 44 and 41 presented higher flow depth than upstream streets 42, 45 and 47, as shown in Figure 19. Runoff on surface and underground accumulated at downstream in DDM. The sewer got filled up, overflowing back to streets.

In addition, DDM could reach similar street flow and sewer flow at downstream as SWMM. The difference in sewer and street flow between DDM and SWMM became less at downstream, because the sewer reached its capacity and no water could enter it. Inlet interception in DDM becomes sewer capacity control at downstream especially during major storms, according to Figure 20, which is similar to the case in SWMM. It infers that DDM could reach similar street flow and sewer flow at downstream as SWMM if the watershed is large enough.

6.3.3 Model Size

Large model area may be better for DDM application. First of all, small area may introduce bigger error at the border. John Street Watershed is a small watershed and the model only considers runoff inside its boundary. All flows outside the boundary are neglected. So there may be more upstream street inflow and there may also be more downstream street outflow. Secondly, larger area will incorporate more downstream effect, which could reduce the difference between SWMM and DDM. So larger watershed area may be a good focus for future model application.

6.4 GI Application

The runoff from watershed would be least with low percent imperviousness, large sewer pipe diameters and better soil hydraulic properties. According to Figure 25 and Figure 26, percent imperviousness had biggest influence on total surface runoff volume. Unit change in %impervious resulted in approximately 0.3 unit change in total surface runoff. In addition, overland runoff is also sensitive to soil type parameters like suction head, hydraulic conductivity, depression storage, porosity and effective saturation, as shown in Figure 25 and Figure 26. These findings indicated high potential of GI application.

6.5 Potential of DDM

Based on the results and discussions, the potentials of DDM are listed below:

- DDM could generate results in surface overland flow, surface street flow and underground sewer flow. It allows for interaction between surface flow and sewer flow with restrictions in inlet interception rate. Runoff in DDM vary spatially and temporally.

- DDM works better under major high-intensity storms, by providing the closest total runoff volume as SWMM and a conservative estimation of overland flow and street flow. It is favorable in flooding estimation and risk assessment.
- DDM could provide detailed street flow velocity and depth time series with restricted interaction between major system and minor system. It helps to identify potential flooding area and causes.
- DDM is sensitive to GI properties during minor storm. It is recommended to add GI section in different modules in future works.

CHAPTER 7 CONCLUSION

7.1 Summary

Today, with increasing frequency of major extreme storms, the existing sewer drainage system could no longer convey water out of urban area promptly due to its inadequate capacity. Dual drainage system could provide quick underground sewer drainage during minor storms, as well as adequate storage and reliable drainage on surface land during major storms. It intends to minimize the property damage and economic loss from flooding. Compared to conventional minor sewer system modeling, dual drainage modeling involves a wide array of complex. There are few existing models incorporating minor system with major system as well as taking little computation resources. DDM is a 1D hydrologic-hydraulic model for simulating dual drainage in urban areas (Nanía, León, & García, 2015). The application itself is only 3.14-MB and is easy to set up. It is an innovative model for surface major system, while incorporating SWMM sewer engine. It consists of four modules: rainfall-runoff transformation, 1D flow routing on a street network, inlet interception and sewer routing with SWMM engine. However, there was only one case study and no assessment on the model performance.

Thus, this study aims to fill the gap by analyzing the capacity and uncertainty of DDM. It focused on modeling dual drainage system in John Street Watershed, Champaign IL by DDM during different storms. It tested the model performance of DDM compared to SWMM and the model sensitivity to GI properties. Based on results and discussions, the contributions of this study are summarized in three aspects: i) a new case study of DDM in municipal area, ii) a preference of using DDM in major storms in terms of model method and model performance, iii) a recommendation of adding GI into DDM.

Firstly, a new case study of DDM was successfully conducted for dual drainage system in John Street Watershed at both high impervious urban area and median impervious residential area. The high resolution results in overland flow, street flow and underground sewer flow open up the possibility to determine potential flooding area susceptible to property damage and economic loss. Residents, communities, retailers, city builders, governments and whoever wants to minimize the flooding loss would be willing to be informed of it. In addition, the GIS tool box provided in this study for input data generation could greatly shorten the model setup time and efforts, and further benefit all stake holders. Secondly, a detailed assessment of DDM performance under different storms compared to SWMM is available in this study only, with highlighting on fundamental model method difference. The finding that DDM is favorably used during major storms corresponds to the original intention of dual drainage system, as analyzing flooding in severe rainfall events. The conservative estimation of surface peak flow in DDM accounts for the worst flooding scenario during major storms, which is beneficial to flooding risk assessment. The breakdown of model methods could be a guideline for researchers to understand the principal and capacity of DDM, as well as a reference for programmers to locate the specific module they want to improve in the future. In addition, with detailed model results, researchers could identify the exact location and reason for flooding, for example how flooding could happen at street low elevation node with large sewer pipe underground. It is necessary for city builders to study urban flooding problems, to update municipal infrastructures and to improve community living environment.

Thirdly, this study recommends future improvements of additional GI section, since DDM demonstrated high sensitivity of GI properties during minor storm. Although GI itself has limited capacity during major storms, researchers and city builders could still have an alternative tool other than SWMM to assess the performance of GI and optimize the location of GI.

7.2 Limitation

The main limitation of this study is the lack of observatory data. DDM was only compared with SWMM to the furthest extent. SWMM is one of the widest accepted drainage models. However, it will still be better to calibrate DDM with real data and make inference about the model accuracy.

Another limitation is the variety of case studies. John Street Watershed is a small area with median urbanization. The size of the watershed partially influenced the model results. The analyses for this study are only valid under this circumstance. It will be better if future studies could perform more case studies with different catchment conditions and real rainfall time series.

7.3 Future Work

Future work could be divided into two parts, GI application and more case studies.

Firstly, it is recommended in this study to incorporate GI into existing modules since DDM is sensitive to GI properties. DDM is a Fortran based model. It is easy for programmers to revise the code and add new GI section in corresponding modules like rain gardens in overland module and pervious pavements in the street module. Other improvements may include the assignment of inlet interception rate to account for clogging.

Secondly, more case studies with observatory data are called for model calibration and assessment. With real data, programmers could improve the model engine and researchers could assess the accuracy of DDM. It could provide supports for future usage of DDM during major storm dual drainage modeling.

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APPENDIX: Summary of DDM Model Input Files and Output Files

Table 11 DDM input files summary

File Name	Content	Variables
Control_spec.csv	Control file	
Dat_prec.csv	Project storm (mm/h)	Rainfall Intensity
Discharge_from_planes2.txt	Overland flow input from rainfall time series, result file	Flow Time Series
Blocks_char.csv	Block character	Pervious and Impervious Slope; Pervious and Impervious Manning; Pervious and Impervious Depression Storage; percent imperviousness; Hydraulic conductivity; Effective Saturation; Effective Porosity; Suction Head
Blocks_nodes.csv	Block surrounding nodes	Number of nodes; Nodes that encircle the block (max 8)
Inlets.csv	Inlet character	Coordinates; Inlet Type; Gutter Type; Gutter Length; Curb Length; Width; Height
Inlets_data.csv	Hypothetical inlet character	Coordinates; Inlet Type; Gutter Type; Gutter Length; Curb Length; Width; Height
Input_Hydrographs.csv	Hydrograph for external nodes	
Nodes.csv	Node character	Coordinates; Elevation; Boundary Type
Plot_profile.csv	Consecutive nodes used to plot profile	Node Number
Sewer.csv	Manhole position	Name; Coordinates

File Name	Content	Variables
Streets.csv	Street character	Upstream Node; Downstream Node; Street Width; Total Width; Gutter Width; Gutter Slope; Street Lateral Slope; Curb Height; Manning's n
Call_swmm.bat	Program file	
Copy_hotstart.bat	Program file	
Param1.txt	Program file	
Read_out_file.bat	Program file	
ReadoutSWMM5_C.exe	Program file	
swmm5.exe	Program file	

Table 12 SWMM INP file summary

Section Name	Variables Notation								
[TITLE]									
[OPTIONS]	flow unit	infiltration method	flow routing method	time	report step	wet step	dry strep	routing step	
[EVAPORATION]	Evap	Data	Parameters						
[RAINGAGES]	Gage	Format	Interval	SCF	Source				
[SUBCATCHMENTS]	Subcatchment	Rain	Gage	Outlet	Area	%Imperv	Width	%Slope	Curb Len
[SUBAREAS]	Subcatchment	N-Imperv	N-Perv	S-Imperv	S-Perv	PctZero	RouteTo	PctRouted	
[INFILTRATION]	Subcatchment	CurveNum	HydCon	DryTime					
[JUNCTIONS]	Junction	Invert	Dmax	Dinit	Dsurch	Aponded			

Section Name	Variables Notation								
[OUTFALLS]	Outfall	Invert	Type	Stage	Data	Gated			
[CONDUITS]	Conduit	From Node	To Node	Length	Roughness	InOffset	OutOffset	InitFlow	Max Flow
[XSECTIONS]	Link	Shape	Geom1	Geom2	Geom3	Geom4	Barrels		
[LOSSES]	Link	Kin	Kout	Kavg	Flap	Gate	SeepRate		
[INFLOWS]	Node	Parameter	Time Series	Param Type	Units Factor	Scale Factor	Baseline Value	Baseline Pattern	
[TIMESERIES]	Time Series	Date	Time	Value					
[REPORT]									
[TAGS]									
[MAP]									
[COORDINATES]	Node	X-Coord	Y-Coord						
[VERTICES]	Link	X-Coord	Y-Coord						
[Polygons]									

Table 13 DDM output files summary

File Name	Content	Detail
RES_CONTROL.txt	Summary of watershed and sewer system input	Plane; nodes; street; inlet; sewer connection and data
depth_nodes_swmm.txt	Sewer depth	Node Depth; HGL
flooded_nodes_swmm.txt	Flooded sewer	Max Flow; flooded Volume; Ponding Depth; Total number of flooded nodes

File Name	Content	Detail
flooding_res2.txt	Summary of flooded_nodes_swmm.txt	Number of flooded nodes; Total flooded flow rate
outfall_swmm.txt	Sewer Outflow	Average flow; Maximum Flow; Total Volume
timeseries_junctions_swmm.txt	Sewer Flow	Sewer inflow or outflow
Inlets_detail.txt	Inlet flow to and from sewer and street	sewer; inlet; street; flow
Inlets.txt	Inlet flow to and from street	street; inlet flow
flooded_nodes_detail.txt	Inlet flow to street	inlet; street; flow
Inlets_sewer.txt	Inlet flow to and from sewer	sewer; inlet flow
flow_discharge.txt	street outflow	street; street connection node; inflow; area; outflow; area; lateral flow; total flow
RES_NODES.txt	street node flow balance	node; depth; previous depth; street; flow; balance
Check_mass.txt	Mass Balance for watershed	Volume existing planes; Volume stored in junctions; Volume stored in streets; volume outflow from streets; volume outflow from inlets; % error
Discharge_from_planes.txt	overland flow from rainfall runoff transformation	street; lateral flow; street flow
RES_STREETS.txt	street flow character	Street; mac depth; max velocity; max y*x; max y*v^2; inflow; outflow; street storage
RES_STREETS2.txt	street hydraulic properties	depth; velocity; Froude number; flow
Plot_Matlab.txt	plotted depth for target streets	time; street; Section; bed elevation; water elevation; velocity; flow

File Name	Content	Detail
Dead_ends_depths.txt	Dead end nodes	street; street connection node; inflow; area; outflow; area; lateral flow; total flow
RES_PLANOS.txt	block mass balance	
Crossings.txt	boundary condition for node	
flooding_out.txt	result of SWMM	inflow; overflow; depth; head; volume; lateral flow
flooding_res.txt	summary of flooding_out.txt	
test_input_swmm.inp	Process file	
hotstart_new.bat	Program file	
Debug_Street_model.txt	Warnings in street model	
INNERPOINTS_STREETS.txt	Inner points in street	
Plot_Matlab_planview.txt	Street depth for target street	
Plot_Matlab_planview2.txt	Street depth for target street	